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Hartley et al.

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(54) **FAST RECONFIGURING ENVIRONMENT FOR MOBILE COMPUTING DEVICES**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 437 days.

This patent is subject to a terminal disclaimer.

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(63) Continuation of application No. 16/022,531, filed on Jun. 28, 2018, now Pat. No. 10,609,076, which is a (Continued)

(51) **Int. Cl.**
H04L 29/06 (2006.01)
G06F 21/53 (2013.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G06F 21/53*** (2013.01); ***G06F 3/067*** (2013.01); ***G06F 3/0622*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC G06F 21/53; G06F 3/0622; G06F 3/0659; G06F 3/0664; G06F 3/067; G06F 21/74;
(Continued)

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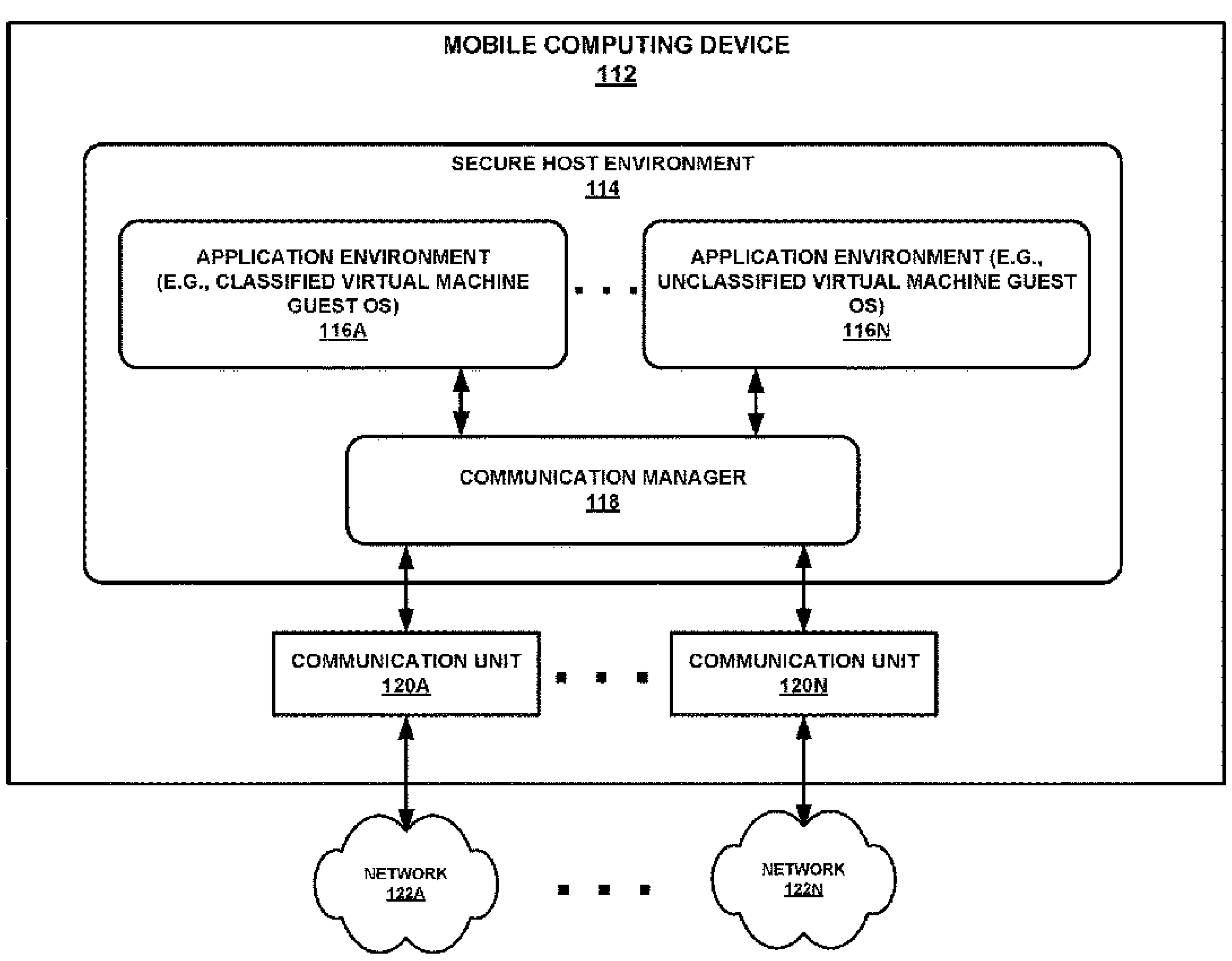
(57) **ABSTRACT**

An example method includes receiving an indication of a selection of a first application environment that includes a first virtual environment associated with a first security domain and is configured to isolate execution of software applications within the first application environment, suspending execution of a second application environment that includes a second virtual environment associated with a second security domain different from the first security domain, initiating execution of the first application environment, identifying information associated with the first security domain and provided by the first application environment that is to be sent to an external computing device associated with the first security domain, selecting communication network(s) from one or more communication networks that are each available to the mobile computing device for data communication, encrypting, based on the first security domain and network(s), the information, and sending, to the external computing device via the network(s), the encrypted information.

16 Claims, 9 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/632,538, filed on Jun. 26, 2017, now Pat. No. 10,015,196, which is a continuation of application No. 15/226,515, filed on Aug. 2, 2016, now Pat. No. 9,769,131.

(51) **Int. Cl.**

H04W 12/033	(2021.01)
G06F 3/06	(2006.01)
H04L 9/40	(2022.01)
H04L 67/00	(2022.01)
G06F 21/74	(2013.01)
H04L 43/0829	(2022.01)
H04L 43/0864	(2022.01)
H04L 43/0882	(2022.01)

(52) **U.S. Cl.**
CPC ***G06F 3/0659*** (2013.01); ***G06F 3/0664*** (2013.01); ***H04L 63/0245*** (2013.01); ***H04L 63/0272*** (2013.01); ***H04L 63/0428*** (2013.01); ***H04L 63/105*** (2013.01); ***H04L 63/18*** (2013.01); ***H04L 67/34*** (2013.01); ***H04W 12/033*** (2021.01); *G06F 21/74* (2013.01); *H04L 43/0829* (2013.01); *H04L 43/0864* (2013.01); *H04L 43/0882* (2013.01)

(58) **Field of Classification Search**
CPC H04W 12/033; H04L 63/0245; H04L 63/0272; H04L 63/0428; H04L 63/10; H04L 63/101; H04L 63/102; H04L 63/105; H04L 63/18; H04L 67/34; H04L 43/0829; H04L 43/0864; H04L 43/0882
See application file for complete search history.

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U.S. Appl. No. 16/022,531, filed Jun. 28, 2018 by Timothy Hartley et al.

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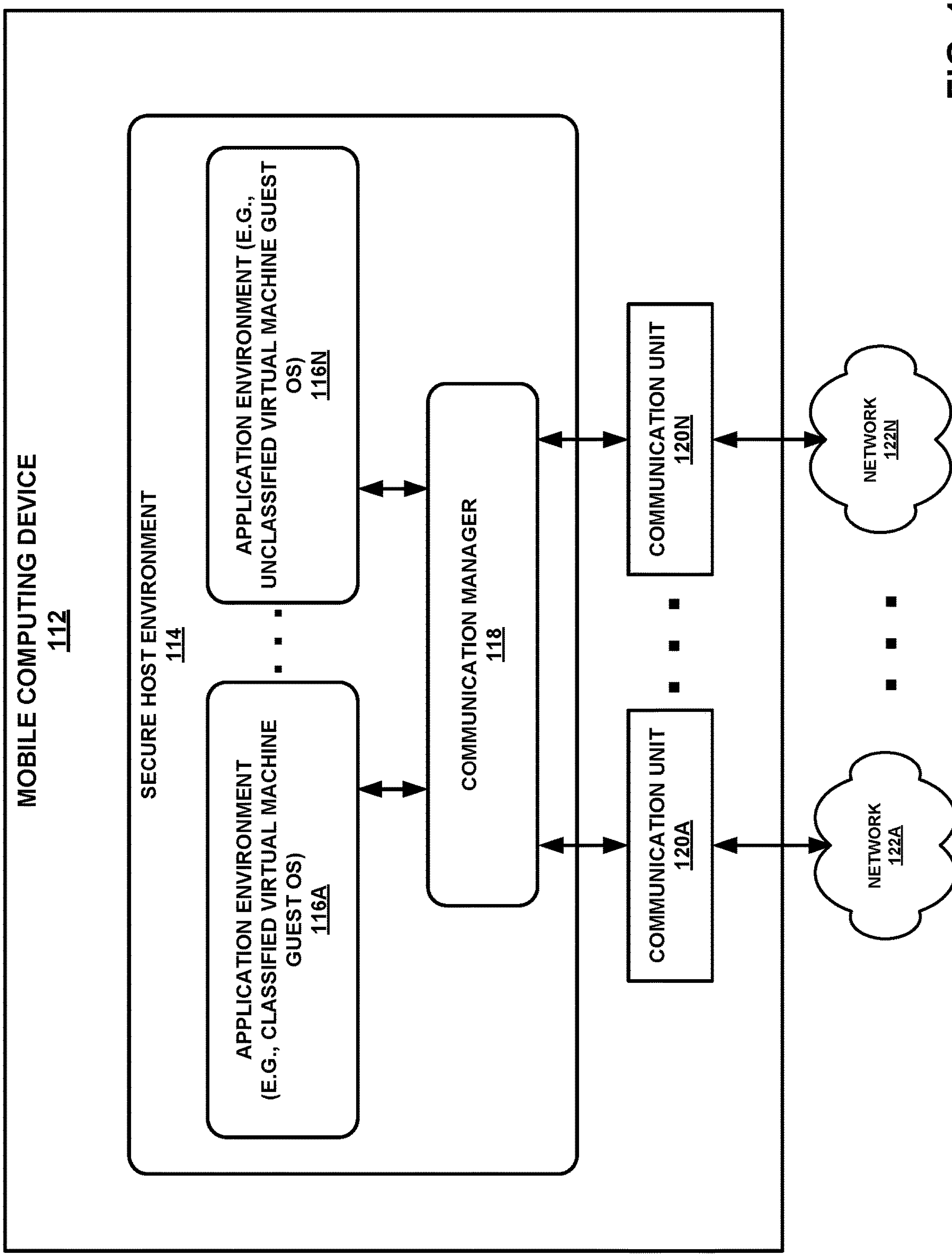

MOBILE COMPUTING DEVICE
112
SECURE HOST ENVIRONMENT
114
APPLICATION ENVIRONMENT (E.G., CLASSIFIED VIRTUAL MACHINE GUEST OS)
116A
APPLICATION ENVIRONMENT (E.G., UNCLASSIFIED VIRTUAL MACHINE GUEST OS)
116N
COMMUNICATION MANAGER
118
COMMUNICATION UNIT
120A
COMMUNICATION UNIT
120N
NETWORK
122A
NETWORK
122N

FIG. 1

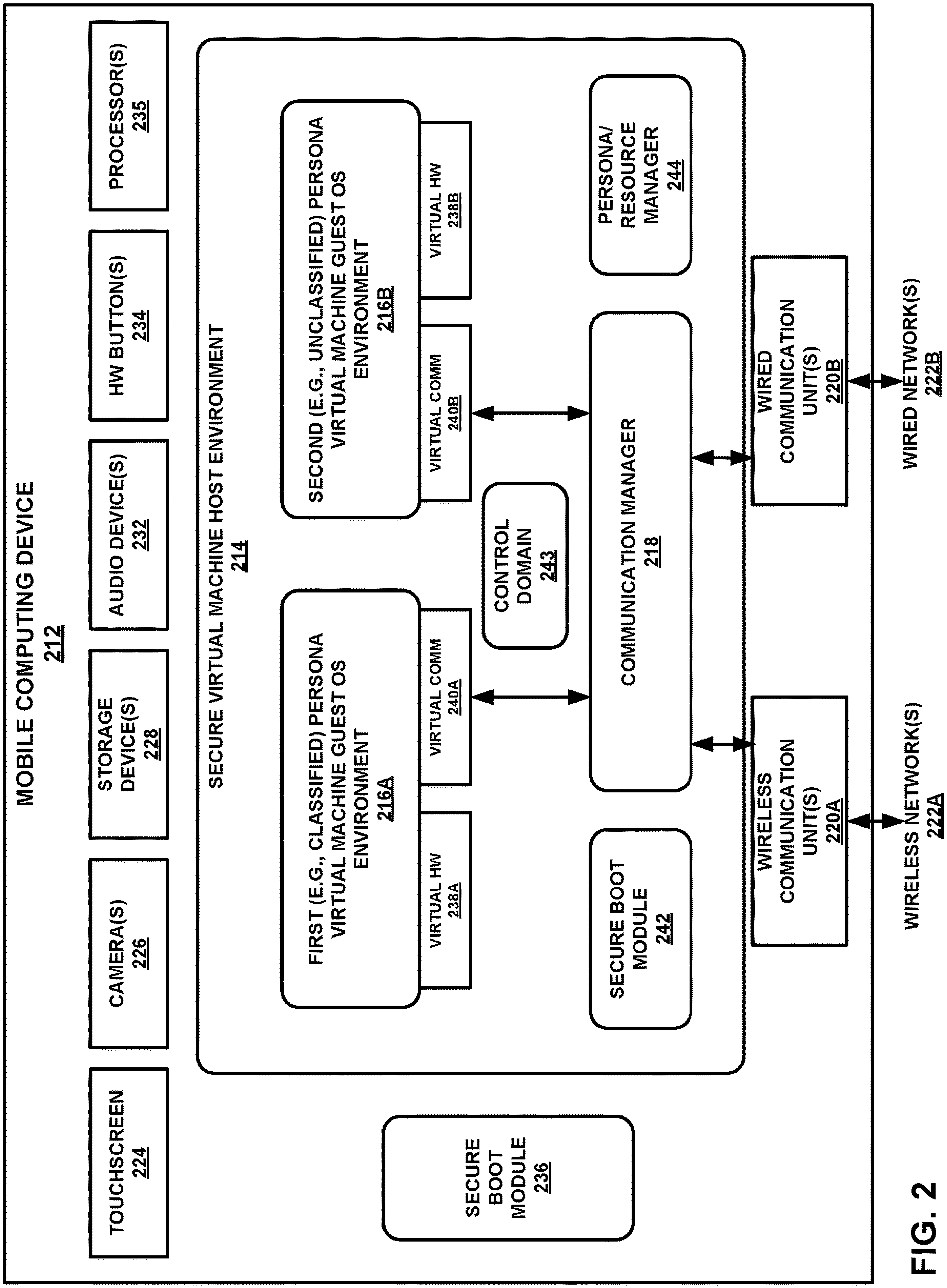
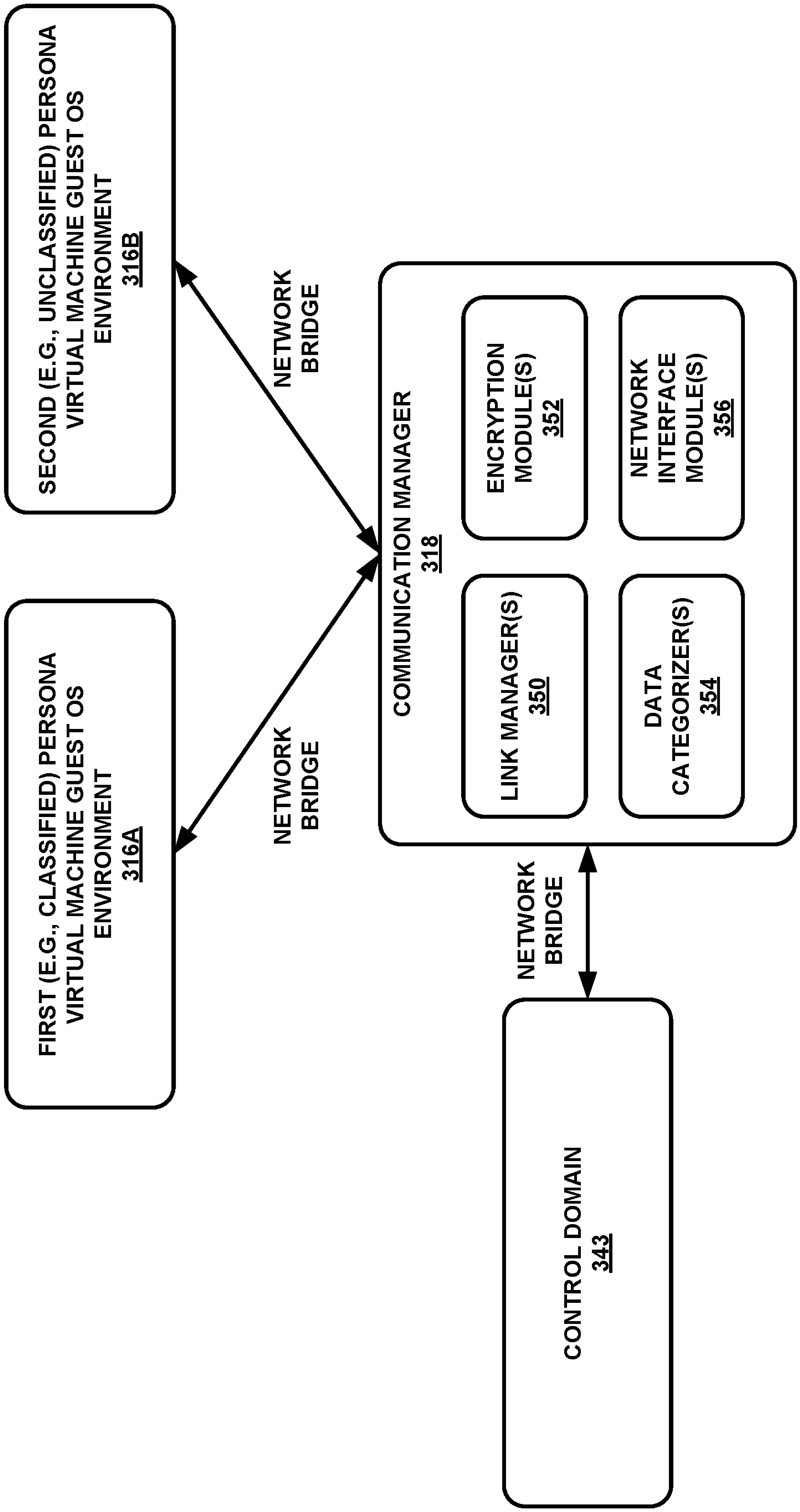

MOBILE COMPUTING DEVICE
212
TOUCHSCREEN
224
CAMERA(S)
226
STORAGE DEVICE(S)
228
AUDIO DEVICE(S)
232
HW BUTTON(S)
234
PROCESSOR(S)
235
SECURE BOOT MODULE
236
SECURE VIRTUAL MACHINE HOST ENVIRONMENT
214
FIRST (E.G., CLASSIFIED) PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT
216A
VIRTUAL HW
238A
VIRTUAL COMM
240A
SECOND (E.G., UNCLASSIFIED) PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT
216B
VIRTUAL COMM
240B
VIRTUAL HW
238B
CONTROL DOMAIN
243
SECURE BOOT MODULE
242
COMMUNICATION MANAGER
218
PERSONA/ RESOURCE MANAGER
244
WIRELESS COMMUNICATION UNIT(S)
220A
WIRED COMMUNICATION UNIT(S)
220B
WIRELESS NETWORK(S)
222A
WIRED NETWORK(S)
222B

FIG. 2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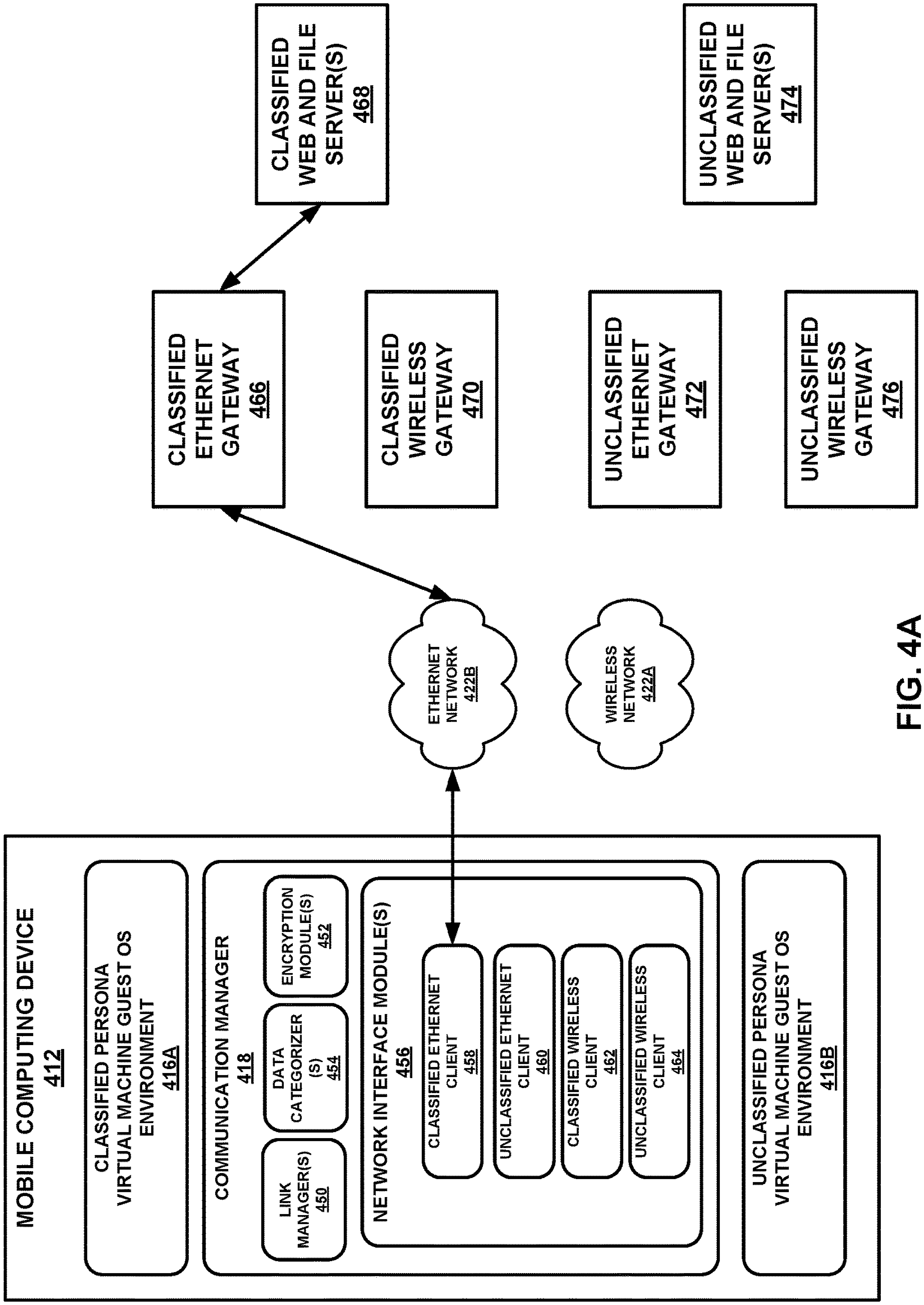
SECOND (E.G., UNCLASSIFIED) PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 316B
NETWORK BRIDGE
NETWORK BRIDGE
COMMUNICATION MANAGER 318
LINK MANAGER(S) 350
ENCRYPTION MODULE(S) 352
DATA CATEGORIZER(S) 354
NETWORK INTERFACE MODULE(S) 356
NETWORK BRIDGE
CONTROL DOMAIN 343

FIG. 3



MOBILE COMPUTING DEVICE 412
CLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416A
COMMUNICATION MANAGER 418
LINK MANAGER(S) 450
DATA CATEGORIZER (S) 454
ENCRYPTION MODULE(S) 452
NETWORK INTERFACE MODULE(S) 456
CLASSIFIED ETHERNET CLIENT 458
UNCLASSIFIED ETHERNET CLIENT 460
CLASSIFIED WIRELESS CLIENT 462
UNCLASSIFIED WIRELESS CLIENT 464
UNCLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416B
ETHERNET NETWORK 422B
WIRELESS NETWORK 422A
CLASSIFIED ETHERNET GATEWAY 466
CLASSIFIED WIRELESS GATEWAY 470
UNCLASSIFIED ETHERNET GATEWAY 472
UNCLASSIFIED WIRELESS GATEWAY 476
CLASSIFIED WEB AND FILE SERVER(S) 468
UNCLASSIFIED WEB AND FILE SERVER(S) 474

FIG. 4A

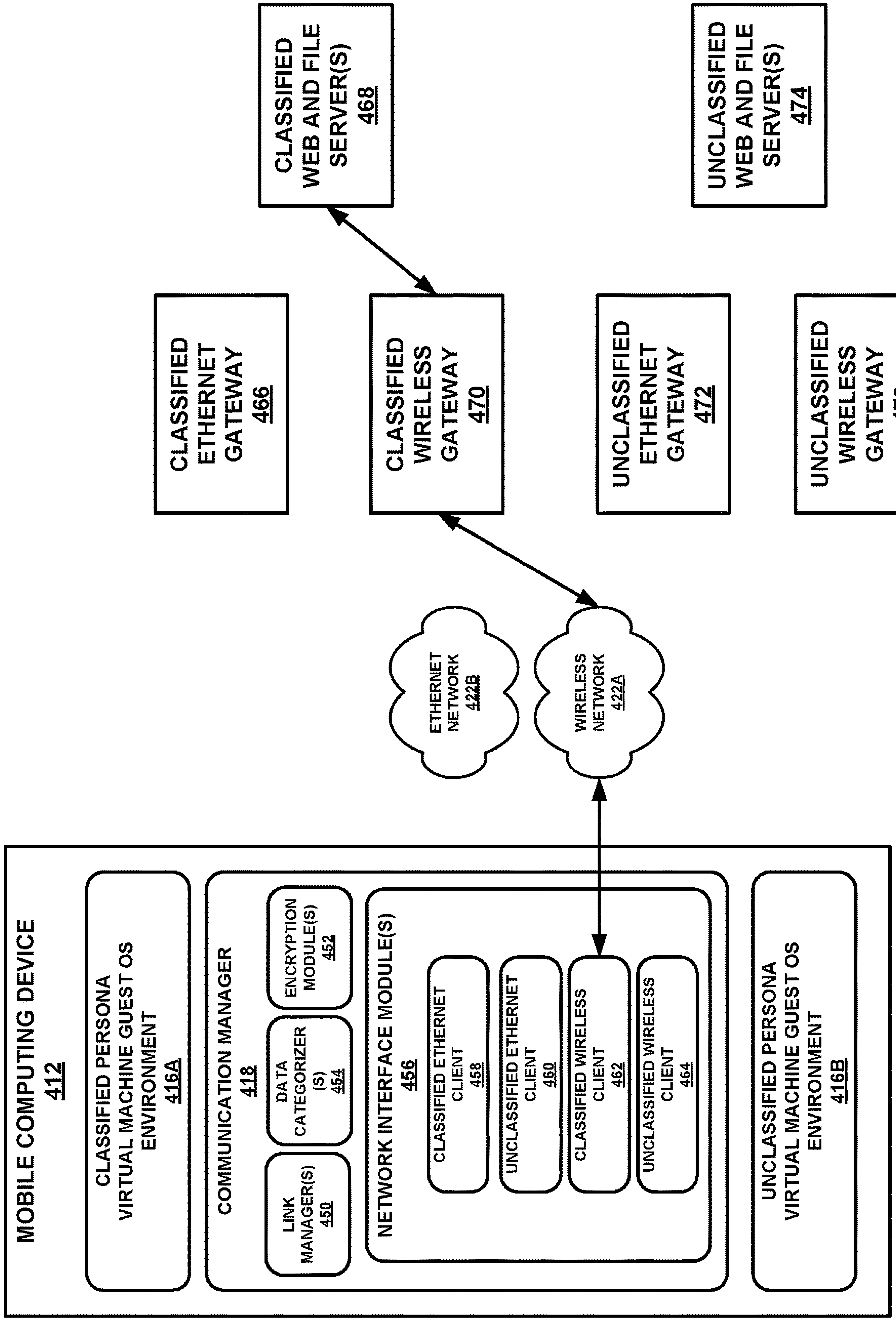

MOBILE COMPUTING DEVICE 412
CLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416A
COMMUNICATION MANAGER 418
LINK MANAGER(S) 450
DATA CATEGORIZER (S) 454
ENCRYPTION MODULE(S) 452
NETWORK INTERFACE MODULE(S) 456
CLASSIFIED ETHERNET CLIENT 458
UNCLASSIFIED ETHERNET CLIENT 460
CLASSIFIED WIRELESS CLIENT 462
UNCLASSIFIED WIRELESS CLIENT 464
UNCLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416B
ETHERNET NETWORK 422B
WIRELESS NETWORK 422A
CLASSIFIED ETHERNET GATEWAY 466
CLASSIFIED WIRELESS GATEWAY 470
UNCLASSIFIED ETHERNET GATEWAY 472
UNCLASSIFIED WIRELESS GATEWAY 476
CLASSIFIED WEB AND FILE SERVER(S) 468
UNCLASSIFIED WEB AND FILE SERVER(S) 474

FIG. 4B

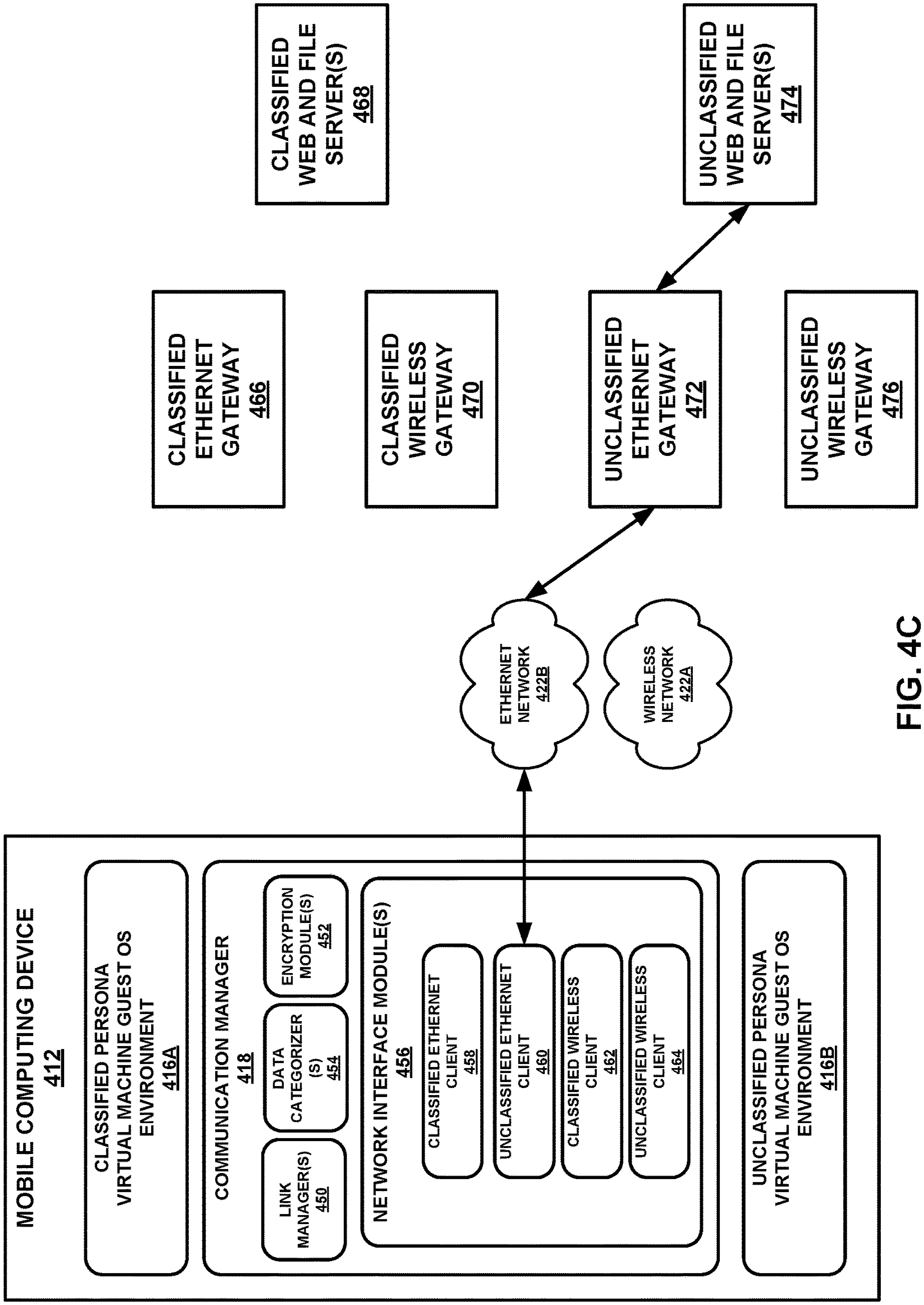

MOBILE COMPUTING DEVICE 412
CLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416A
COMMUNICATION MANAGER 418
LINK MANAGER(S) 450
DATA CATEGORIZER (S) 454
ENCRYPTION MODULE(S) 452
NETWORK INTERFACE MODULE(S) 456
CLASSIFIED ETHERNET CLIENT 458
UNCLASSIFIED ETHERNET CLIENT 460
CLASSIFIED WIRELESS CLIENT 462
UNCLASSIFIED WIRELESS CLIENT 464
UNCLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416B
ETHERNET NETWORK 422B
WIRELESS NETWORK 422A
CLASSIFIED ETHERNET GATEWAY 466
CLASSIFIED WIRELESS GATEWAY 470
UNCLASSIFIED ETHERNET GATEWAY 472
UNCLASSIFIED WIRELESS GATEWAY 476
CLASSIFIED WEB AND FILE SERVER(S) 468
UNCLASSIFIED WEB AND FILE SERVER(S) 474

FIG. 4C

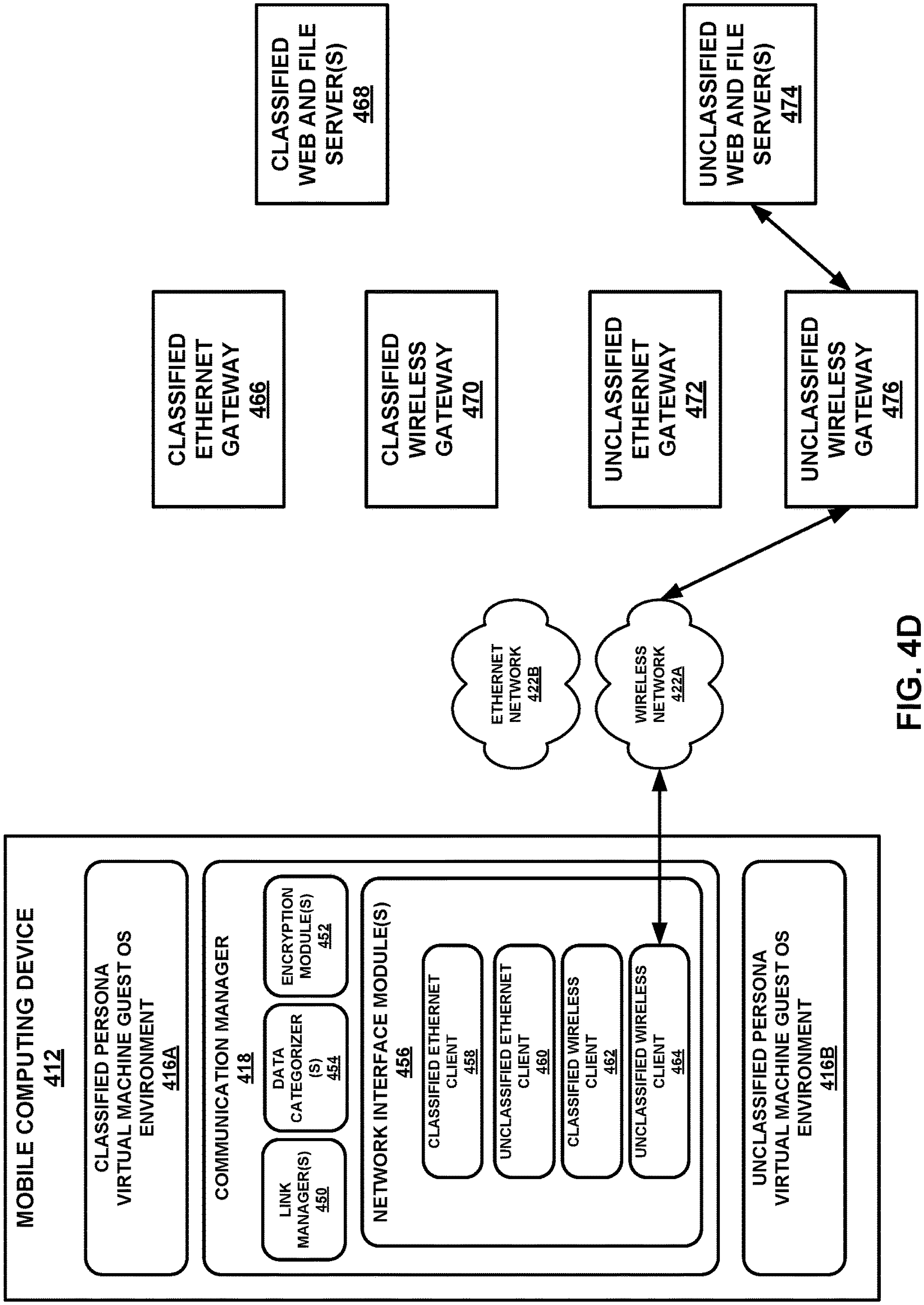

MOBILE COMPUTING DEVICE 412
CLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416A
COMMUNICATION MANAGER 418
LINK MANAGER(S) 450
DATA CATEGORIZER (S) 454
ENCRYPTION MODULE(S) 452
NETWORK INTERFACE MODULE(S) 456
CLASSIFIED ETHERNET CLIENT 458
UNCLASSIFIED ETHERNET CLIENT 460
CLASSIFIED WIRELESS CLIENT 462
UNCLASSIFIED WIRELESS CLIENT 464
UNCLASSIFIED PERSONA VIRTUAL MACHINE GUEST OS ENVIRONMENT 416B
ETHERNET NETWORK 422B
WIRELESS NETWORK 422A
CLASSIFIED ETHERNET GATEWAY 466
CLASSIFIED WIRELESS GATEWAY 470
UNCLASSIFIED ETHERNET GATEWAY 472
UNCLASSIFIED WIRELESS GATEWAY 476
CLASSIFIED WEB AND FILE SERVER(S) 468
UNCLASSIFIED WEB AND FILE SERVER(S) 474

FIG. 4D

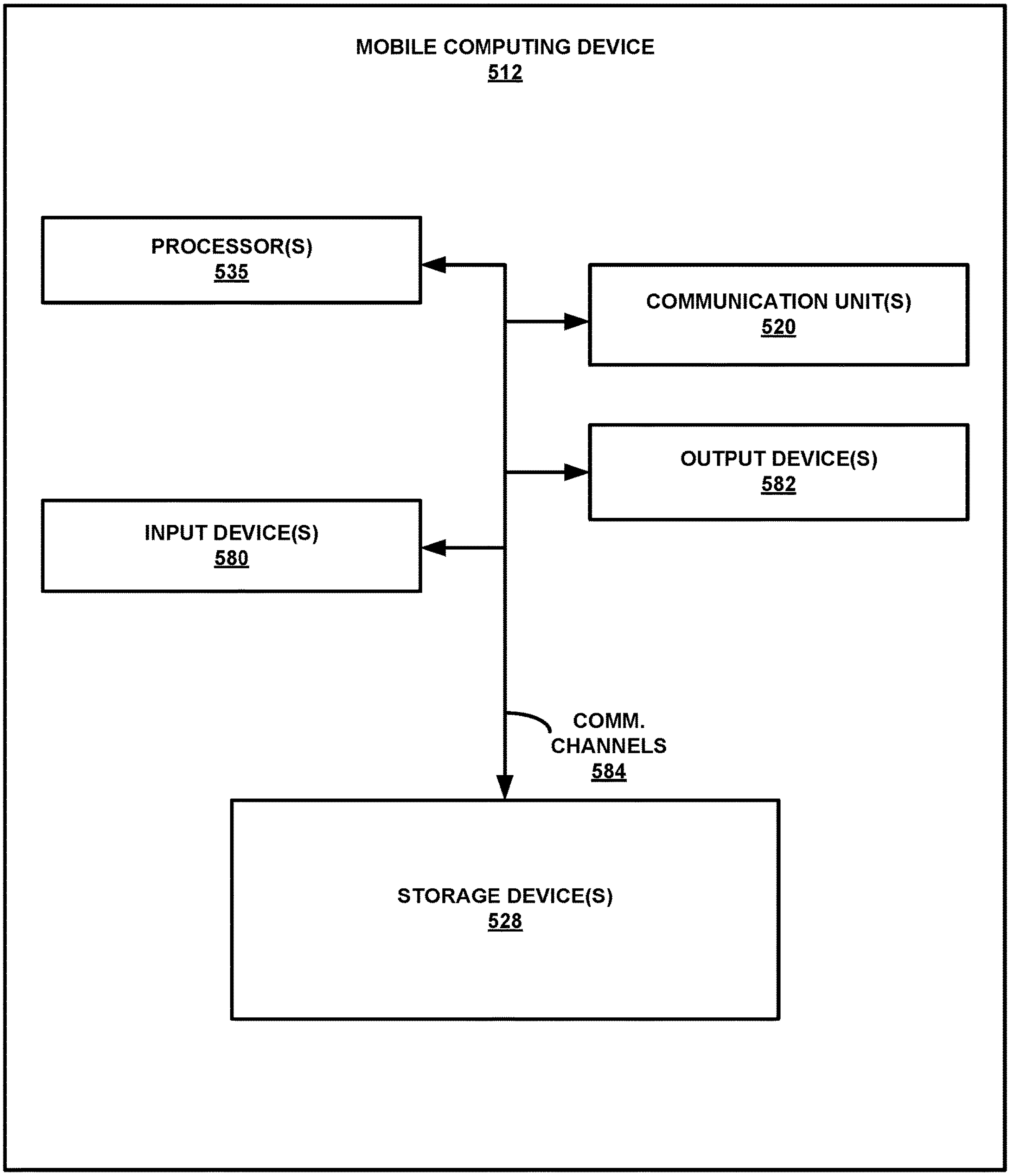

MOBILE COMPUTING DEVICE
512
PROCESSOR(S)
535
COMMUNICATION UNIT(S)
520
OUTPUT DEVICE(S)
582
INPUT DEVICE(S)
580
COMM.
CHANNELS
584
STORAGE DEVICE(S)
528

FIG. 5

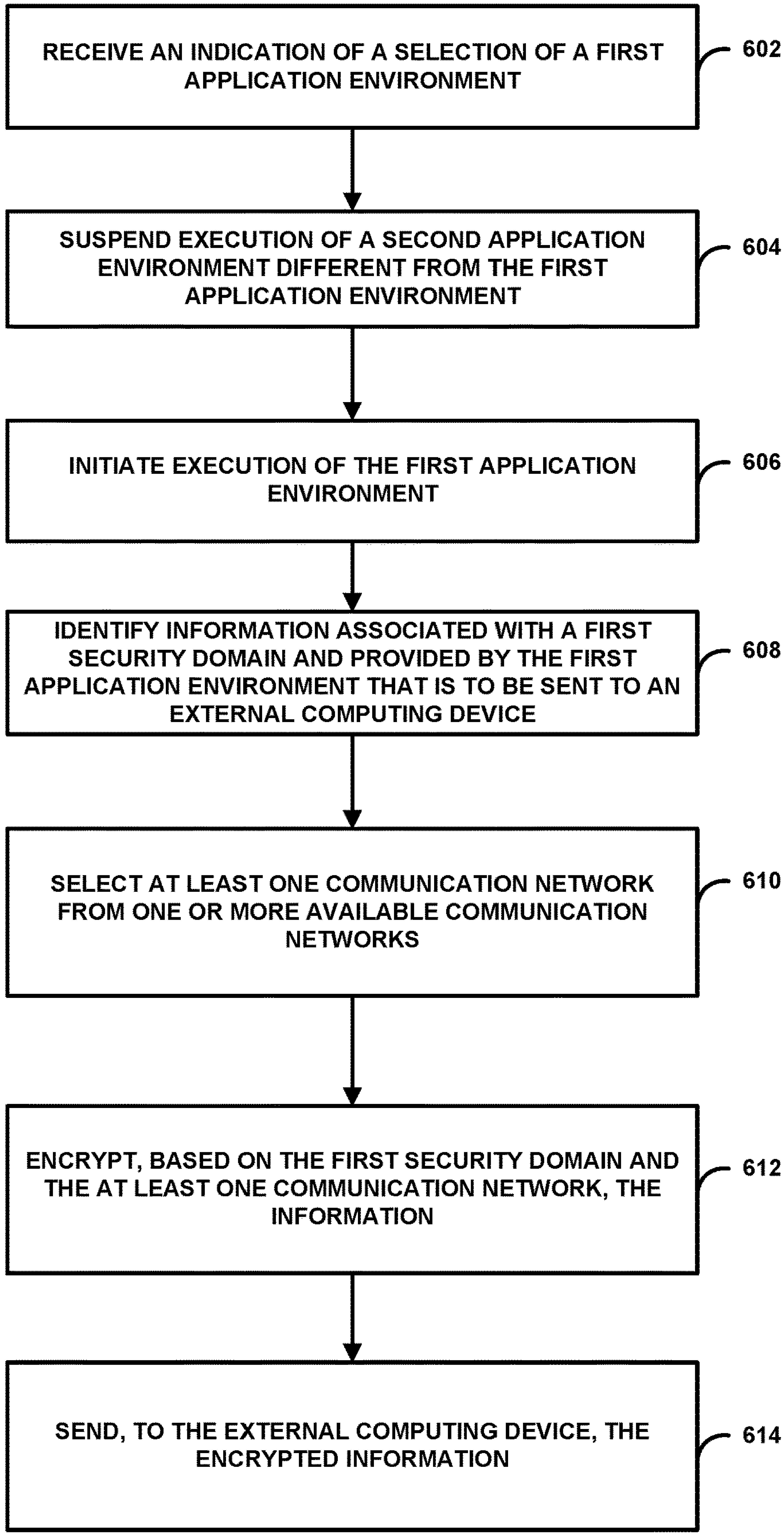

RECEIVE AN INDICATION OF A SELECTION OF A FIRST APPLICATION ENVIRONMENT
602
SUSPEND EXECUTION OF A SECOND APPLICATION ENVIRONMENT DIFFERENT FROM THE FIRST APPLICATION ENVIRONMENT
604
INITIATE EXECUTION OF THE FIRST APPLICATION ENVIRONMENT
606
IDENTIFY INFORMATION ASSOCIATED WITH A FIRST SECURITY DOMAIN AND PROVIDED BY THE FIRST APPLICATION ENVIRONMENT THAT IS TO BE SENT TO AN EXTERNAL COMPUTING DEVICE
608
SELECT AT LEAST ONE COMMUNICATION NETWORK FROM ONE OR MORE AVAILABLE COMMUNICATION NETWORKS
610
ENCRYPT, BASED ON THE FIRST SECURITY DOMAIN AND THE AT LEAST ONE COMMUNICATION NETWORK, THE INFORMATION
612
SEND, TO THE EXTERNAL COMPUTING DEVICE, THE ENCRYPTED INFORMATION
614

FIG. 6

FAST RECONFIGURING ENVIRONMENT FOR MOBILE COMPUTING DEVICES

This application is a continuation of U.S. application Ser. No. 16/022,531, filed Jun. 28, 2018, which is a continuation of U.S. application Ser. No. 15/632,538, filed Jun. 26, 2017 (now U.S. Pat. No. 10,015,196), which is a continuation of U.S. application Ser. No. 15/226,515, filed Aug. 2, 2016 (now U.S. Pat. No. 9,769,131), all of which are incorporated herein by reference in their entireties.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with Government support under N68335-15-C-0374 awarded by the Department of the Navy. The Government has certain rights in this invention.

BACKGROUND

Today, users increasingly rely on computing devices, such as mobile computing devices, for voice communication, information access, and application usage. However, untrustworthy applications and certain online behaviors can potentially compromise the security of such computing devices. The continuing adoption of mobile computing devices in various organizations has created a growing desire for technologies that enable device users to separate their data into different categories use, such as, for example, classified and unclassified data.

SUMMARY

In one example, a method includes receiving, by a mobile computing device that includes one or more processors, an indication of a selection of a first application environment from a plurality of application environments, wherein the first application environment includes a first virtual environment that is associated with a first security domain, and wherein the first application environment is not currently executing on the mobile computing device. The example method further includes, responsive to receiving the indication of the selection of the first application environment, suspending, by the mobile computing device, execution of a second application environment from the plurality of application environments, wherein the second application environment is different from the first application environment, and wherein the second application environment includes a second virtual environment that is associated with a second security domain different from the first security domain. After suspending execution of the second application environment, the example method further includes initiating, by the mobile computing device, execution of the first application environment on the mobile computing device, wherein the first application environment is configured to isolate execution of one or more software applications within the first application environment, and identifying, by the mobile computing device, information associated with the first security domain and provided by the first application environment that is to be sent to an external computing device associated with the first security domain. The example method further includes selecting, by the mobile computing device, at least one communication network from one or more communication networks that are each available to the mobile computing device for data communication, wherein selecting the at least one communication network is based on one or more criteria associated with at least one of

the information associated with the first security domain or the one or more communication networks. The example method further includes encrypting, by the mobile computing device, based on the first security domain and the at least one selected communication network, the information to generate encrypted information associated with the first security domain, and sending, by the mobile computing device and to the external computing device, via the at least one selected communication network, the encrypted information.

In one example, a mobile computing device includes one or more processors and a computer-readable storage device communicatively coupled to the one or more processors. The computer-readable storage device stores instructions that, when executed by the one or more processors, cause the one or more processors to: receive an indication of a selection of a first application environment from a plurality of application environments, wherein the first application environment comprises a first virtual environment that is associated with a first security domain, and wherein the first application environment is not currently executing on the mobile computing device; responsive to receiving the indication of the selection of the first application environment, suspend execution of a second application environment from the plurality of application environments, wherein the second application environment is different from the first application environment, and wherein the second application environment comprises a second virtual environment that is associated with a second security domain different from the first security domain; after suspending execution of the second application environment, initiate execution of the first application environment on the mobile computing device, wherein the first application environment is configured to isolate execution of one or more software applications within the first application environment; identify information associated with the first security domain and provided by the first application environment that is to be sent to an external computing device associated with the first security domain; select at least one communication network from one or more communication networks that are each available to the mobile computing device for data communication, wherein selecting the at least one communication network is based on one or more criteria associated with at least one of the information associated with the first security domain or the one or more communication networks; encrypt, based on the first security domain and the at least one selected communication network, the information to generate encrypted information associated with the first security domain; and send, to the external computing device, via the at least one selected communication network, the encrypted information.

In one example, a computer-readable storage device stores instructions that, when executed, cause a mobile computing device having one or more processors to perform operations. The operations include receiving an indication of a selection of a first application environment from a plurality of application environments, wherein the first application environment comprises a first virtual environment that is associated with a first security domain, and wherein the first application environment is not currently executing on the mobile computing device, and, responsive to receiving the indication of the selection of the first application environment, suspending execution of a second application environment from the plurality of application environments, wherein the second application environment is different from the first application environment, and wherein the second application environment comprises a second virtual environment that is associated with a second security domain different from the first security domain. The operations further include, after suspending execution of the second application environment, initiating execution of the first application environment on the mobile computing device, wherein the first application environment is configured to isolate execution of one or more software applications within the first application environment. The operations further include identifying information associated with the first security domain and provided by the first application environment that is to be sent to an external computing device associated with the first security domain, and selecting at least one communication network from one or more communication networks that are each available to the mobile computing device for data communication, wherein selecting the at least one communication network is based on one or more criteria associated with at least one of the information associated with the first security domain or the one or more communication networks. The operations further include encrypting, based on the first security domain and the at least one selected communication network, the information to generate encrypted information associated with the first security domain, and sending, to the external computing device, via the at least one selected communication network, the encrypted information.

The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the disclosure will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a block diagram illustrating an example mobile computing device that is configured to provide support for multiple different application environments, or personas, in a secure host environment, in accordance with one or more aspects of the present disclosure.

FIG. **2** is a block diagram illustrating further details of one example of the mobile computing device shown in FIG. **1**, in accordance with one or more aspects of the present disclosure.

FIG. **3** is a block diagram illustrating further example details of a communication manager, in accordance with one or more aspects of the present disclosure.

FIGS. **4**A-**4**D are block diagrams illustrating example flows of information from a communication manager of a mobile computing device to external classified and unclassified servers, in accordance with one or more aspects of the present disclosure.

FIG. **5** is a block diagram illustrating further details of an example mobile computing device, in accordance with one or more aspects of the present disclosure.

FIG. **6** is a flow diagram illustrating an example process that may be performed by a computing device, such as the mobile computing device shown in FIG. **1**, FIG. **2**, FIGS. **4**A-**4**D, and/or FIG. **5**, and/or a mobile computing device that includes the communication manager shown in FIG. **3**, in accordance with one or more aspects of the present disclosure.

DETAILED DESCRIPTION

As noted above, untrustworthy applications and certain online behaviors can potentially compromise the security of computing devices. To be secure and useful, a computing device may, in many cases, provide multi-level security and accessibility to services. Current mobile device management solutions may not meet the needs of existing systems. The techniques of the present disclosure describe software-based systems that may enable multi-level access and/or security across different domains (e.g., classified and unclassified domains), protecting data from accidental or intentional leakage between security domains. These computing systems may be implemented on various types of mobile computing devices, such as smartphones and tablet computers.

In various examples described herein, a mobile computing device may provide independent application environments, or personas, for different security domains. As described herein, the multiple, independent application environments of the mobile computing device may enable potentially fast transition between personas, efficient allocation and reallocation of memory and persistent storage according to need and priority, and/or secure management of communication media and device communication according to application and end-point criteria, such as to minimize latency, maximize bandwidth, and, in various cases, prioritize traffic according to data type. As a result, the mobile computing device described herein may be configured to intelligently allocate processor usage, memory, and storage to an active (e.g., high priority) persona, while transparently suspending a background (e.g., low priority) persona to free resources and preserve rapid access. In addition, the mobile computing device may intelligently select from among available off-device communication paths in an effort to prioritize data, maximize bandwidth, optimize latency, protect data security, and abstract changes to connectivity.

Thus, the techniques of the present disclosure may, in various examples, implement a high-assurance virtualization environment that hosts multiple isolated personas and abstracts hardware and communication access. These techniques may further oversee the switching of personas, controlling the allocation and reallocation of resources to personas, as well as the sanitization of memory and persistent storage prior to reallocation. A communication manager executing on the mobile computing device may perform intelligent analysis of data packets and available communication media, including characterizing the available bandwidth and latency and differing endpoint connectivity, to optimize media use and application responsiveness.

FIG. **1** is a block diagram illustrating an example mobile computing device **112** that is configured to provide support for multiple different application environments, or personas, in a secure host environment **114**, in accordance with one or more aspects of the present disclosure. As illustrated in FIG. **1**, mobile computing device **112** may be configured to provide a secure host environment **114**, where mobile computing device **112** includes a group of communication units **120**A-**120**N (collectively, "communication units **120**). Communication units **120** are configured to communicate with different communication networks **122**A-**122**N, respectively (collectively, "networks **122**"). Communication networks **122** may comprise one or more physical communication networks.

Secure host environment **114** may, in some examples, comprise a virtual machine host environment that hosts one or more virtual machines. As shown in FIG. **1**, secure host environment **114** includes a group of application environments **116**A-**116**N (collectively, "application environments **116**) and a communication manager **118**. Secure host environment **114** provides the framework for supporting and isolating distinct application environments, or personas, **116**. For instance, as one non-limiting example, application environment **116**A may be configured to handle classified data and applications and to communicate with classified networks, while application environment **116**N, which is separate and distinct from application environment **116**A, may be configured to handle unclassified data and applications and to communicate with unclassified networks. As will be described in the example of FIG. **2**, application environments **116** and communication manager **118** may each be implemented as guest virtual machines or containers under the control of secure host environment **114**.

Application environments **116** may, in various examples, have little to no direct hardware access in mobile computing device **112**, where communication instead is directed through communication manager **118**. Communication manager **118** is capable of providing load balancing, transparent fail-over when media communication is interrupted, and/or tunneling (e.g., virtual private network (VPN) tunneling), when available, to leverage communication media at different security levels, depending on which of application environments **116** is an active environment. In some cases, such as shown in FIG. **2**, secure boot functionality is also provided in mobile computing device **112** and/or secure host environment **114**, and secure host environment **114** may also include an application environment/resource manager or managers, as described in further detail below.

Secure host environment **114** may use hardware virtualization to maintain strict control over resource allocation, hardware access, communication, and security. Each application environment of application environments **116** may, as noted above, comprise a virtual machine guest encompassing a complete operating system (OS), applications, and data storage to create a standalone environment at a particular security level. In other examples, some or all of a given application environment (e.g., one of application environments **116**, communication manager **118**) may comprise a virtual container that may or may not execute a complete guest operating system separate from a host operating system of mobile computing device **112**. In some cases, each of application environments **116** may have no cross-domain data path, and storage space provided by mobile computing device **112** may be allocated separately for each of application environments **116**. Secure host environment **114** may encrypt all storage, protecting itself and application environments **116**.

In some examples, secure host environment **114** may include an application environment/resource manager, such as persona/resource manager **244** shown in FIG. **2**. Such an application environment/resource manager may, in various cases, enable a user of mobile computing device **112** to switch from, e.g., an active foreground application environment (e.g., application environment **116**A) to a different application environment (e.g., application environment **116**N), such as by the user interacting with a hardware or graphical user interface element (e.g., button) provided by mobile computing device **112**. According to one or more examples of the present disclosure, by assuming exactly one active application environment (e.g., persona) at any given moment, various resources of mobile computing device **112** (e.g., processors, memory) may be fully available to certain foreground tasks, helping ensure an optimal user experience. Such an implementation may also simplify security domain isolation by eliminating back-channel communication between domains that are associated with application environments **116**. As one example, if one of application environments **116** transitions from an active to an inactive (e.g., suspended) state, such as application environment **116**A, state information of any resources utilized by this application environment **116**A (e.g., processors, memory) may be stored to data stores (e.g., encrypted and/or persistent storage), and can be reloaded in potentially short order when application environment **116**A becomes active once again. In addition, communication manager **118** and/or a resource manager (e.g., persona/resource manager **244** shown in FIG. **2**) may prohibit any communication with an inactive persona.

This approach allows application environments **116** to be switched potentially more responsively than would be possible if every switch resulted in a reboot of a guest operating system associated with one or more of application environments **116**, and allows application environments **116** to be started quickly even after a power down event. The application environment/resource manager may also oversee memory and persistent storage allocation, reserving constrained resources of mobile computing device **112** and determining resource needs of application environments **116** over time, prior to allocation. In some examples, one or more of application environments **116** may be active at a given time. Much of the state information of an individual one of application environments **116** may exist within, e.g., its virtual disk image, except for, in certain cases, ephemeral state residing in main memory and peripherals, such as disk caches or hardware registers, which may be flushed and/or reset when a given application environment is moved to an inactive state.

Communication manager **118** of secure host environment **114** may perform various different functions. First, communication manager **118** enables the respective operating systems of application environments **116** to operate with a defined concept of available communication networks available to mobile computing device **112**, so these operating systems and their contained applications do not necessarily need to react to varying connectivity as mobile computing device **112** moves from one connectivity domain to another. Communication manager **118** may also be configured to utilize one or more algorithms to optimize message delivery from application environments **116** to computing devices external to mobile computing device **112**, as well as providing load balancing. In addition, in one or more examples, communication manager **118** may provide at least two-layer encryption of data, such as described in further detail below, and may also ensure that mobile computing device **112** communicates only via authenticated gateways to networks appropriate to the active application environment of application environments **116**. For example, if application environment **116**A is active and is associated with a classified domain, communication manager **118** may determine that traffic originating from application environment **116**A is directly forwarded to classified networks. If, however, load balancing criteria and/or current connectivity state indicates that the currently available and/or best route (e.g., lower latency and/or higher bandwidth) is via a secure but unclassified network, communication manager **118** may determine to encrypt and forward all data via a virtual private network (VPN) gateway. In this example, application environment **116**A does not necessarily need to be aware of the VPN or of the route taken by the communication.

In certain non-limiting examples, as will be described in further detail below, persona/resource manager **244** and/or communication manager **118** may receive an indication of a selection of a first application environment from application environments **116**. This first application environment may comprise a first virtual environment (e.g., virtual machine environment, container) that is associated with a first security domain, and the first application environment may not be currently executing on mobile computing device **112**. At a particular point in time, secure host environment **114** may be reconfigured so this first application environment becomes active, while a second application environment of application environments **116** may be transitioned from an active to inactive state (e.g., based on input from an application environment/resource manager, such as persona/resource manager **244** shown in FIG. **2**). Secure host environment **114** may, responsive to receiving the indication of the selection of the first application environment, suspend execution of the second application environment, where the second application environment is different from the first application environment, and where the second application environment comprises a second virtual environment (e.g., virtual machine environment, container) that is associated with a second security domain different from the first security domain. Contemporaneously, communication manager **118** may reconfigure to prevent communication to and from the second application environment via communication units **120**.

After suspending execution of the second application environment, secure host environment **114** may initiate execution of the first application environment, where the first application environment may be configured to isolate execution of one or more software applications within the first application environment, and communication manager **118** may be configured to identify information associated with the first security domain and provided by the first application environment that is to be sent to an external computing device associated with the first security domain. In addition, communication manager **118** may select one or more communication networks from communication networks **122** that are available to mobile computing device **112** for data communication. The selecting may be based on one or more criteria associated with at least one of the information associated with the first security domain or communication networks **122**. Communication manager **118** may encrypt, based on the first security domain and the selected communication network(s), the information to generate encrypted information that is associated with the first security domain, and send, to the external computing device, via the selected communication network(s) (e.g., using one of communication units **120**), the encrypted information.

As a result, the techniques of the present disclosure may improve usability of mobile computing device **112**. Application environments **116** may comprise independent environments or personas that are respectively associated with different security domains having separate operating systems, configurations, applications, and data securely isolated in each respective domain. Different operating systems and/or types of operating systems may be provided in different ones of application environments **116**. The use of secure host environment **114** may enable a potentially fast transition between active and inactive states for respective ones of application environments **116** to allow efficient access to applications and data in different respective domains. Secure host environment **114** may suspend a currently active application environment of application environments **116** to move it from an active to inactive state, and may also unsuspend a currently inactive application environment of application environments **116** to move it from an inactive to an active state.

The techniques may also provide both data-at-rest encryption and data-in-transit encryption. Data-at-rest encryption may be imposed without involvement by the user of mobile computing device **112** and/or application environments **116** to ensure data is secure. By utilizing such data-at-rest encryption, in various examples, mobile computing device **112** to be treated as "unclassified" when powered off when application environments **116** include both an "unclassified" and a "classified" environment. In some cases, data-at-rest encryption conforms with Commercial Solutions for Classified (CSfC) guidelines. Communication manager **118** may be further configured to provide data-in-transit encryption, presenting virtual communication interfaces to application environments **116** and enforcing redirection of network communication from application environments **116** to any available communication media, regardless of security level, and employing CSfC-compliant encryption of data-in-transit in certain cases. Data-in-transit encryption may enable communication from applications in an application environment at one security classification to transit media at a different classification (e.g., subject to VPN availability).

Communication manager **118** is also configured, in certain examples, to ensure that each one of application environments **116** is limited to sending or receiving communications within its respective security domain. Application environments **116** and/or communication manager **118** may also support dynamic data type tagging or categorization, and management of all available communication media in an effort to minimize latency, maximize bandwidth, and prioritize traffic according to data type, as described in further detail below. With respect to dynamic data type tagging or categorization, communication manager **118** enables dynamic categorization of data between application environments **116** and external media to allow policies to be applied according to, e.g., priority and latency considerations.

FIG. **2** is a block diagram illustrating further details of an example mobile computing device **212**, which is one non-limiting example of mobile computing device **112** shown in FIG. **1**, in accordance with one or more aspects of the present disclosure. Mobile computing device **212** includes a secure virtual machine host environment **214**, which is one example of secure host environment **114** shown in FIG. **1**. Mobile computing device **212** also includes one or more wireless communication units **220**A and one or more wired communication units **220**B, which are examples of communication units **120** shown in FIG. **1**. Mobile computing device **212** uses wireless communication units **220**A to communicate with one or more wireless networks **222**A, and mobile computing device **212** uses wired communication units **220**B to communicate with one or more wired networks **222**B. Wireless networks **222**A and wired networks **222**B (collectively, "networks **222**") are examples of communication networks **122** shown in FIG. **1**.

Mobile computing device **212** further includes a secure boot module **236**, which will be described in further detail below. In addition, mobile computing device **212** includes a touchscreen **224**, one or more cameras **226**, one or more processors **235**, one or more storage devices **228** (which may include memory), one or more audio devices **232**, and, in some examples, one or more hardware buttons **234**. Audio devices **232** may include one or more input (e.g., microphone) and/or output (e.g., speaker) audio devices. Storage devices **228** store data used by secure boot module **236** and secure virtual machine host environment **214**, including first persona **216**A and second persona **216**B. Storage devices **228** may also store data used by or associated with any of the other elements included in mobile computing device **212** shown in FIG. **2**. In addition, storage devices **228** may store instructions that are executable by one or more processors of mobile computing device **212** to implement the functionality of secure boot module **236** and secure virtual machine host environment **214** (including first persona **216**A, second persona **216**B, secure boot module **242**, communication manager **218**, and/or persona/resource manager **244**).

First persona **216**A and second persona **216**B may each comprise a virtual machine guest operating system (OS) environment provided in secure virtual machine host environment **214**, and may be examples of application environment **116**A and **116**N shown in FIG. **1**. First persona **216**A and second persona **216**B may provide distinct operating system environments that may implement either the same of different operating systems. Secure virtual machine host environment **214** employs an environment to provide the basis for supporting and isolating two distinct personas, namely first persona **216**A and second persona **216**B. First persona **216**A may be configured to handle classified data and applications and to communicate directly with classified networks, while second persona **216**B may be configured to handle unclassified data and applications and to communicate directly with unclassified networks.

In various examples, first persona **216**A, second persona **216**B, communication manager **218**, and persona/resource manager **244** may be isolated as guest virtual machines under the control of the secure virtual machine host environment **214**. Personas **216**A and **216**B may have no direct hardware access, and all communication is directed through communication manager **218**, such as described in reference to FIG. **1**. First persona **216**A may provide a virtual hardware interface **238**A and a virtual communication interface **240**A, while second persona **216**B may provide a virtual hardware interface **238**B and a virtual communication interface **240**B. First persona **216**A communicates with communication manager **218** via virtual communication interface **240**A, while second persona **216**B communicates with communication manager **218** via virtual communication interface **240**B. Communication manager **218** may implement load balancing, transparent fail-over when media communication is interrupted, and VPN tunneling when available to leverage a communication media at a different security level than the active persona (e.g., one of first persona **216**A or second persona **216**B).

Communication manager **218** may operate in a separate execution domain with respect to personas **216**A, **216**B, and may control respective virtualized communication channels between communication manager **218** and personas **216**A, **216**B to limit access by personas **216**A, **216**B to one or more resources of mobile computing device **212**. For example, communication manager **218** may control one or more virtualized communication channels with persona **216**A via virtual communication interface **240**A, and may control one or more virtualized communication channels with persona **216**B via virtual communication interface **240**B. Virtual hardware interface **238**A may serve as an interface to one or more resources of mobile computing device **212** that may be made available to persona **216**A, and virtual hardware interface **238**B may serve as an interface to one or more resources of mobile computing device **212** that may be made available to persona **216**B.

Secure virtual machine host environment **214** may use hardware virtualization to maintain strict control over resource allocation, hardware access, communication, and security. Each persona **216**A, **216**B may be a virtual machine encompassing a complete operating system, applications, and data storage needed to create a standalone environment at a particular security level. Secure boot module **236** of mobile computing device **212** may provide secure boot functionality to serve as a hardware root of trust. Secure boot module **236** may include a Trusted Platform Module (TPM) and may also provide full-disk encryption. The TPM helps ensures that the hardware virtualization solution is tamper-proof by checking cryptographically created signatures for the bootloader and kernel. Full-disk encryption helps ensure encryption of data at rest (e.g., CSfC compliant encryption), which can be implemented efficiently with, e.g., a single additional layer of software encryption. Secure boot module **236** may prevent any unauthorized, modified software from being booted on mobile computing device **212**, which may allow backdoors or password capture to be introduced. The TPM may, in various examples, implements secure key storage for key encryption keys to ensure no keys are usable except following user verification and to verify all keys used by secure virtual machine host environment **214** are generated by an approved authority. Secure boot module **236** verifies that the initial boot software is signed by a trusted authority, as well, and also that the software has not been modified after being signed.

Secure virtual machine host environment **214** may include its own secure boot module **242**. Secure boot module **242** may include software that calculates secure hashes of software components and personas (e.g., first persona **216**A and second persona **216**B), and securely verifies signatures before loading components or starting personas. To do this, according to one or more examples, a CSfC approved digital signature algorithm, such as Elliptic Curve Digital Signature Algorithm (ECDSA), may be employed to generate signatures for each software component in secure virtual machine host environment **214** using a secret key. These signatures can be verified on every boot before the respective component is used. Only the public key used for verifying the signature may be located or stored on mobile computing device **212**. The signing key may not be kept on mobile computing device **212**, according to various examples. Similar signing may be performed on persona disk images to detect unauthorized modification, and this functionality may be performed by persona/resource manager **244**.

Persona/resource manager **244** enables a user to switch from an active foreground persona to a different persona for the foreground e.g., at the touch of a hardware button or via another form of user interaction with mobile computing device **212**, such as via a graphical user interface. If a graphical user interface is provided by mobile computing device **212** (e.g., using touchscreen **224**), persona/resource manager **244** may control the display and input while the user makes choices. In one or more examples, by providing exactly one active persona, secure virtual machine host environment **214** helps enable an optimal user experience, because various resources (e.g., processors, memory) are fully available to foreground tasks. Secure virtual machine host environment **214** also simplifies security domain isolation by eliminating back-channel communication between domains, but can, in some examples, allow multiple personas at the same classification level (e.g., multiple different classified or unclassified personas) to be active at the same time. When a persona transitions from an active to an inactive state, the state of the active persona may be snapshotted to encrypted persistent storage, and may be reloaded once the persona becomes active again. This approach allows personas to be switched more responsively than would be possible if every switch required a reboot of a guest operating system, and allows personas to be started quickly even after a power down event. Persona/resource manager **244** also oversees the memory and persistent storage allocation, reserving constrained resources and determining persona needs over time before allocating them.

As described previously, secure virtual machine host environment **214** enables multiple distinct operating system environments to operate, presented as personas **216**A and **216**B, which address different operational needs. Personas **216**A and **216**B are isolated from each other and from any hardware access that could allow data to transit between security domains, especially communication media.

In certain non-limiting examples, one or more of personas **216**A or **216**B implements a Linux guest operating system. Control domain **243** provides control of secure virtual machine host environment **214** and the guest operating systems implemented by personas **216**A and **216**B. In certain non-limiting examples, secure virtual machine host environment **214** comprises a virtualization hypervisor (e.g., a Xen virtualization hypervisor). Xen can be used as a Type-1 hypervisor, allowing the hypervisor attack surface to be kept small. Control domain **243** may be executed in a virtual machine run under Xen, with communication channels defined by the Xen application programming interface.

In certain non-limiting examples, creating a persona (e.g., first persona **216**A, second persona **216**B) may be a multi-step process, which may be performed in secure virtual machine host environment **214** or control domain **243** via configuration and/or via user input. First, a configuration file specific to a single virtual machine (e.g., persona) may be created. This configuration file may specify memory size of the virtual machine and a virtual disk image representing the virtual machine hard drive. A virtual disk image may be created. This image can, in some cases, be either one or more physical partitions, separate from the host operating system but on the same or different physical disk drive, or it can be one or more file images, which may be treated as a disk drive that is partitionable. A virtual install media image may then be booted, and the operating system may be installed to the virtual disk image. Alternatively, a byte-wise copy of an existing disk image or physical partition can be performed to create a duplicate of an existing bootable virtual machine. The virtual disk image may then be booted.

In one example, Xen optionally provides direct access to Peripheral Component Interconnect (PCI) peripherals. Control domain **243** may, in some examples, use this option to provide one or more of personas **216**A, **216**B direct access to a graphics card of mobile computing device **212**, which may provide three-dimensional graphics rendering acceleration or other performance improvements.

As noted above, each persona **216**A, **216**B may have a virtual disk image, and this image can, in some cases, be either one or more physical partitions, separate from the host operating system but on the same or different physical disk drive, or it can be one or more file images, which may be treated as a disk drive that is partitionable. In various examples, control domain **243** will provide file images as the virtual disk images for personas **216**A and **216**B. Disk image files may be created and replaced administratively, facilitating administrative oversight of mobile computing device **212**, such as pushing updated, clean versions of personas **216**A and/or **216**B when, for example, operating systems or applications are to be updated. In some examples, secure virtual machine host environment **214** or control domain **243** may also support image overlays and appending multiple files to increase the storage available to a persona filesystem by specifying multiple files in the individual persona's virtual machine configuration file. These may be presented by secure virtual machine host environment **214** to persona **216**A or **216**B as a single filesystem, despite existing as separate disk image files in the secure virtual machine host environment **214** filesystem. In addition, file images located in the secure virtual machine host environment **214** filesystem may be subject to software full disk encryption, as described in further detail below.

While overlays provide one approach to expanding the storage available to persona **216**A or **216**B, an alternative is to create multiple images as disk partitions that can be mounted by the persona operating system at mount points in its filesystem. The configuration file specific to a given persona (e.g., persona **216**A or **216**B) may allow disk images to be either read-only or read-write, and may allow different disk images to be presented as different disk partitions to the persona. Secure virtual machine host environment **214** can use this ability to protect persona applications and the base operating system from changes.

In some examples, secure virtual machine host environment **214** may enable one-way communication of information via virtualized storage and between personas **216** by assigning different access rights (e.g., read-only, read-write) to different ones of personas **216**. For example, second (e.g., unclassified) persona **216**B may be able to effectively share data with first (e.g., classified) persona **216**A, even if only one of personas **216**A or **216**B is active at a given time. In this example, using a selected hardware virtualization solution would allow different configurations mounting the same virtual disk image (e.g., partition) as, e.g., read-only in persona **216**A and read-write in persona **216**B. The virtual disk image may be encrypted appropriately for, e.g., classified data storage using the same approach as the personas.

In some examples, mobile computing device **212** may use two independent layers of encryption, namely hardware full-disk encryption and software full-disk encryption. Two different methods of protecting encryption keys may also be used in mobile computing device **212**: a password and a smartcard. In these examples, because all guidelines in the CSfC Data-At-Rest Capability Package are followed, including key protection and secure boot, mobile computing device **212** can be handled as unclassified equipment when powered off or when running an unclassified persona (e.g., second persona **216**B). In certain examples, secure boot module **236** may perform at least a portion of the hardware full-disk encryption. In some examples, secure virtual machine host environment **214** or control domain **243** may perform at least a portion of the hardware and/or software full-disk encryption.

Software full-disk encryption may be applied in control domain **243** (e.g., Xen control domain) to all partitions. Different encryption keys may be used for different partitions, if persona virtual disk images are stored on separate partitions, and loaded in control domain **243** when needed. The software full-disk encryption keys may be protected by a user smartcard or common access card (CAC), while the hardware full-disk encryption may be protected by a user password. By using the smartcard to protect software full-disk encryption, secure virtual machine host environment **214** enables the user to switch personas without necessarily needing to re-enter a user password to unlock additional keys for different partitions.

Communication manager **218** may, in many examples, handle all network data sent and received by mobile computing device **212**. One purpose of communication manager **218** is to ensure that data communication from and to mobile computing device **212** is not only secure but also leverages available communication media (e.g., available networks, such as one or more wireless networks **222**A and one or more wired networks **222**B shown in FIG. **2**) in an efficient manner.

Communication manager **218** may implement various security features. Communication manager **218** may encrypt data using the correct encryption keys based on the source of data itself, which is the current active persona (e.g., persona **216**A or **216**B). For example, if first persona **216**A is a persona associated with classified domain data, communication manager **218** may encrypt any data sent from first persona **216**A using one or more encryption keys associated with this particular classified domain. If second persona **216**B is a persona associated with unclassified domain data, communication manager **218** may encrypt any data sent form second persona **216**B using one or more encryption keys associated with this particular unclassified domain.

Communication manager **218** may provide data isolation, such that data communication cannot be leaked from one persona to the other. Communication manager **218** may also provide one or more firewalls to prevent any unauthorized external network access (e.g., attempted access via wireless networks **222**A or **222**B) to mobile computing device **212**. Based on administrative control provided by communication manager **218**, communication manager **218** may also ensure that certain kinds of traffic can only be routed through a specific communication medium (e.g., via wired network **222**B), or inside a specific network setting. Such functionality may be based or dependent on which of personas **216**A or **216**B is currently active.

Communication manager **218** may also implement various features in efforts to optimize network resource utilization for mobile computing device **212**, such as link failover and load balancing. For example, for link failover, if one link fails or suffers degradation in quality, communication manager **218** may switch to another or better link based on type of traffic and link metrics. For example, if first persona **216**A is currently the active persona, and communication manager **218** is currently using one of wireless communication units **220**A to send data from first persona **216**A to one of wireless networks **222**A, it is possible that this wireless network may experience a failure. In this case, if one of wired networks **222**B is available, communication manager **218** may switch and use one of wired communication units **220**B to send data from first persona **216**A to this wired network. Communication manager **218** may also switch, in some cases, to another one of wireless networks **222**A if available.

For link failover situations, depending on the scenario and the configuration, communication manager **218** may, in some cases, transparently create a new VPN client for one of wireless communication units **220**A or wired communication units **220**B to tunnel encrypted traffic to a VPN gateway appropriate for the data type and link. For example, if first persona **216**A is a classified persona, and communication manager **218** uses wireless communication units **220**A or wired communication units **220**B to send data from first persona **216**A to a classified server using an unclassified network (e.g., one of wireless networks **222**A or wired networks **222**B), communication manager **218** may tunnel encrypted traffic to a VPN gateway that is communicatively coupled to this classified server.

Communication manager **218** may also implement load balancing across available ones of wireless networks **222**A and wired networks **222**B, utilizing one or more load-balancing techniques, criteria, or algorithms, such as techniques, criteria, and/or algorithms known in the art. If more than one link is available at a given time, both of them can, in some cases, be used simultaneously to increase the overall bandwidth available to mobile computing device **212**. Communication manager **218** may also allow different types of traffic from persona **216**A or **216**B to go through different links (e.g., wireless networks **222**A, wired networks **222**B) based on the optimal or selected link for data type or traffic originating from persona **216**A or **216**B. To do so, communication manager **218** may identify the type of data sent from persona **216**A or **216**B based on data tagging, as will be described in further detail below. Communication manager **218** may also, in some examples, continuously estimate bandwidth, latency, and packet loss based on monitoring persona traffic or additional algorithms so that potentially the best media is used at all times from mobile computing device **212**.

Communication manager **218** may work with the persona/resource manager **244** to ensure transparent and secure transition of communications when switching from one persona to the other. When a persona is inactive, communication manager **218** may disable all communication from/to that persona, sanitize the network stack, and unload the configuration and encryption keys associated with that persona's communication. The communication paths for the inactive persona may be disabled in parallel with freezing the operating state/file image of the persona, to be completed before the next persona is started and activated in some examples, guaranteeing that data communication is isolated and that data from different personas do not traverse overlapping paths.

In various examples, communication manager **218** may comprise a virtual machine to isolate communication control from other parts of secure virtual machine host environment **214**. In these examples, after the secure boot module **236** boots mobile computing device **212**, secure virtual machine host environment **214** (e.g., using control domain **243**) starts communication manager **218** before starting persona **216**A or **216**B. Communication manager **218** has responsibility for all communication, including communication via control domain **243**. Communication devices of mobile computing device **212** may not be accessible in control domain **243**. In some examples, if persona/resource manager **244** is remotely configurable, even control domain communication passes through communication manager **218** and may be secured by data-in-transit encryption (e.g., CSfC compliant data-in-transit encryption) and gateway authentication enforced by communication manager **218**. Thus, in various examples, communication manager **218** may be executed in a virtual environment on mobile computing device **212**, which is isolated from application environments (e.g., personas **216**) and user control or modification. Communication manager **218** may be subject to modification by secure, encrypted communications with a remote administrative device, which is remote from mobile computing device **212**.

In various examples, persona/resource manager **244** may provide multiple services running in control domain **243** (e.g., Xen control domain), which may have direct access to hardware of mobile computing device **212** that is not available to personas **216**A, **216**B. In certain non-limiting examples, configuration of persona/resource manager **244** and/or communication manager **218** may be privileged and performed either by an administrator with physical possession of mobile computing device **212** or by authorized personnel via a secure remote connection to mobile computing device **212**.

Persona/resource manager **244** may have various functions or responsibilities, such as persona switching between personas **216**A and **216**B (including hardware sanitization and data-at-rest key management), persona resource allocation oversight, and/or persona filesystem protection and signature validation. Persona switching is triggered automatically or by a user when the user wishes to change the active persona from one of persona **216**A or **216**B to the other of persona **216**A or **216**B (e.g., via a graphical user interface or a hardware button, such as one of hardware buttons **234**).

Persona/resource manager **244** may also be responsible for managing data-at-rest encryption, such as, for example, by employing two layers of encryption involving hardware full-disk encryption and software full-disk encryption. Security may be further implemented by employing different disk partitions for each persona **216**A and **216**B, with different encryption keys for each partition. Persona/resource manager **244** can load and unload encryption keys associated with software full-disk encryption depending on which persona is active, making the data of inactive personas safely encrypted and inaccessible to other personas. Encryption keys may be protected by different factors (e.g., two factors in compliance with the CSfC guidelines) for protecting encryption keys differently for different layers. The hardware full-disk encryption may, e.g., require a password to unlock the keys protecting the hard disk. The software full-disk encryption may, e.g., be integrated with smartcard support, requiring the user's smartcard or other similar mechanism to be physically plugged into mobile computing device **212** to unlock the software encryption keys. When a persona switch occurs, persona/resource manager **244** may write the snapshot file to the partition containing the main persona filesystem for the outgoing persona, and then unload the related encryption keys. A snapshot file may encompass the transitory state of a virtual machine (e.g., persona) including, e.g., random access memory, central processing unit state, hardware peripheral registers and memory, and/or other state information. It may then load the encryption keys for the incoming persona and load the snapshot file associated with the new persona.

Persona/resource manager **244** may also oversee any direct hardware access provided to the active persona. Any hardware device that is not fully virtualized or emulated by control domain **243** may be re-initialized to ensure that no data leakage occurs. Cleanup involves unloading and loading device modules and issuing other operating system commands that control hardware. This might involve saving the state information of a hardware device and then sanitizing it before allocating it to the next persona.

An alternative to saving the state information and restoring the state of hardware by persona/resource manager **244** is to have the guest operating system of persona **216**A or **216**B perform this in its space, using its virtual hard disk for storage, by inducing the persona operating system to invoke its hibernate or sleep function before persona/resource manager **244** uses control domain **243** to suspend the persona state. The hardware may still be sanitized by persona/resource manager **244**. When a persona switch occurs, persona/resource manager **244** may notify communication manager **218** so it can disable communication pathways not applicable to the new active persona and change data categorization and prioritization policies based on the active persona.

Persona/resource manager **244** also oversees allocating and reallocating resources. It does this, according to certain examples, by creating virtual disk image files in control domain **243**, which can then be uniquely assigned to persona **216**A or **216**B (e.g., via a persona-related configuration file). Persona/resource manager **244** may be responsible for allocating additional virtual disk image files and for modifying the configuration for a specific persona to add new disk images to the persona disk configuration. Personas **216**A and/or **216**B may also monitor disk usage and induce persona/resource manager **244** to add new virtual disk space. Persona/resource manager **244** can also use the capabilities of control domain **243** (e.g., Xen configuration) to mount additional virtual disk files at specific mount points within a root filesystem to present additional storage to a given persona. This may, in certain cases, be useful for certain types of data (e.g., mission specific data), where after data loses value, a smaller virtual disk file can be mounted in its place and the old virtual disk file can be deleted to free up the disk space for other personas. Such an operation could be performed either at the behest of an administrator, or possibly in coordination with a user application running in each persona, which may only have the ability to release mounted virtual disks associated with that particular persona. Sanitization may be performed on release. Persona/resource manager **244** may also modify a persona's configuration when additional memory is needed.

Persona/resource manager **244** may also be configured to oversee the security of personas **216**A and **216**B. For example, persona/resource manager **244** may generate cryptographic hash signatures for inactive persona filesystems and verify they are not changed between activations. Persona/resource manager **244** may also apply read-only protection from control domain **243** to portions of the persona filesystem that should not change. The persona filesystems are in control domain **243**, in non-limiting examples in which persona/resource manager **244** operates using virtual disk images for persona **216**A and/or **216**B. When an active persona is suspended, the virtual disk image associated with the persona may be static and a cryptographic hash function can generate a signature that can be checked before the persona is next active. Because the cryptographic hash function may, in some cases, be slow compared to persona switching, the signature may, in these cases, be checked as a background task, and any unexpected change may cause functions of persona/resource manager **244** to mark the respective persona as compromised and to be unwilling to restart the persona. File permissions can be used to change the persona related files to read-only during the time when the persona is not active, such as to protect it from change. In such fashion, an active persona may be prohibited from modifying the virtual disk image associated with the inactive persona.

In various non-limiting examples, a directory containing read-only files, such as /bin or /lib, may be moved from a primary disk image file to a separate disk image file, and may be subsequently configured read-only in the configuration file of control domain **243** for the persona **216**A or **216**B. The disk image file for the root filesystem may be mounted read-write, and read-only directories can be added by configuration as additional "disk partitions" to be mounted by the persona operating system. Read-only virtual disk images may have signatures generated once by persona/resource manager **244**.

In non-limiting examples, read-only protection of system files can, in some cases, involve multiple layers (e.g., four layers) of protection from three roles: the persona (e.g., persona **216**A or **216**B), control domain **243**, and the control domain filesystem where virtual disk images are stored. For example, the following four layers of protection may be provided via the following: (1) the file permissions in the persona operating system marks each file that it is read-only; (2) the persona mount configuration mounts the disk partition (represented to control domain **243** as a virtual disk image, but to the persona as a partition) as a read-only mount; (3) the persona virtual machine configuration specifies the disk image file is read-only, so control domain **243** refrains from writing changes to the disk image; and (4) the host filesystem permission can mark the disk image file as read-only, so the host operating system refrains from writing changes to the disk image.

In these non-limiting examples, of the four layers, two may be enforced by the persona operating system. The third layer uses capabilities of control domain **243** to externally enforce file modification permissions, and the fourth layer uses the host operating system. These enforcement mechanisms may, in many cases, not be circumvented by a persona user or process. This layered protection of data access provides an opportunity for safe cross-domain data access overseen secure virtual machine host environment **214**. A disk image file could be allocated to represent storage for data exchange. Data exchange may, in some cases, only be allowed from, e.g., an unclassified persona to a classified persona. This disk image file can be specified as read-only access in the classified persona, but as read-write in the unclassified persona. It may be mounted as a disk partition at some mount point in both personas. Because the image access is read-only for the classified persona, externally enforced by control domain **243**, there is minimal-to-no risk of data flowing from the classified persona to the unclassified persona, including through back-channels. This is because the classified persona is prohibited from modifying the disk image file. In addition, because only one persona may be active at a time (according to various examples), and because only the unclassified persona is performing writes in this example, there may be no risk of disk image corruption.

FIG. **3** is a block diagram illustrating further example details of a communication manager **318**, in accordance with one or more aspects of the present disclosure. Communication manager **318** may be one example of communication manager **118** (FIG. **1**) or communication manager **218** (FIG. **2**). FIG. **3** illustrates communication manager **318**, control domain **343**, first persona **316**A, and second persona **316**B. Control domain **343** may be one example of control domain **243** shown in FIG. **2**. First persona **316**A and second persona **316**B may be examples of first persona **216**A and second persona **216**B, respectively, as shown in FIG. **2**.

As illustrated in FIG. **3**, communication manager **318** is communicatively coupled to control domain **343**, e.g., via an internal network bridge that connects virtual network interfaces in both domains. Communication manager **318** is also communicatively coupled to first persona **316**A and second persona **316**B via respective internal network bridges. Similar to first persona **216**A, first persona **316**A shown in FIG. **3** may comprise a virtual machine guest OS environment that is associated with a classified security domain. Similar to second persona **216**B, second persona **316**B shown in FIG. **3** may comprise a virtual machine guest OS environment that is associated with an unclassified security domain.

In various examples, only one respective network bridge is visible to or usable by a given persona **316**A or **316**B, and all communication for the persona **316**A or **316**B is handled through its respective bridge regardless of the number or the availability of external network links available to communication manager **318**. Each persona **316**A and **316**B may use a respective virtual communication interface (e.g., interface **240**A, **240**B shown in FIG. **2**) to communicate with communication manager **318** via a respective network bridge. Communication manager **318** also maintains a network bridge to communicate control and configuration messages with control domain **343**.

As shown in FIG. **3**, communication manager **318** includes one or more link managers **350**, one or more encryption modules **352**, one or more data categorizers **354**, and one or more network interface modules **356**. Each respective encrypt module of encryption modules **352** is responsible for initiating and configuring any VPN tunnels to ensure all data communication is secured and, in some cases, conforming to the CSfC guidelines. In some examples, each persona **316**A and **316**B has its own corresponding encryption module in communication manager **318**. In these examples, encryption modules **352** include at least two different modules—a first encryption module for first persona **316**A, and a second encryption module for second persona **316**B. If first persona **316**A is a persona associated with a classified security domain, the corresponding first encryption module of encryption modules **352** is responsible for encrypting data provided by first persona **316**A using appropriate keys and/or algorithms associated with this classified security domain. Similarly, if second persona **316**B is a persona associated with an unclassified security domain, the corresponding second encryption module is responsible for encrypting data provided by second persona **316**B using appropriate keys and/or algorithms associated with this unclassified security domain.

In addition to encrypting all data communication, extra measures may be taken to harden the security of communication manager **318**. For example, firewalls may be used to protect communication manager **318** from any unauthorized access. To help prevent leakage of information between personas **316**A and **316**B, in some cases, only the network resources (e.g., network bridge, devices) and the encryption module of encryption modules **352** associated with the currently active persona are kept active. When a persona is inactive, its network bridge is disabled in control domain **343**, and its respective VPN tunnel is disabled by the respective encryption module of encryption modules **352**. From that point on, in various examples, no communication may be possible in or out of that persona until it is activated again and all of its network and VPN configuration are restored by control domain **343** and communication manager **318**.

Communication manager **318** may use certificate pinning to maintain signed and validated certificates for each of its VPN gateways (e.g., gateways illustrated in FIGS. **4**A-**4**D). When establishing a VPN tunnel, the certificate presented by the gateway, at the other end of a possible VPN tunnel, is checked against the one pinned by communication manager **318**. The tunnel may, in many examples, be created only if the certificate passes validation by communication manager **318**. This check may be performed on all links for all configured gateways.

To further isolate the communication paths of first and second personas **316**A and **316**B, communication manager **318** may use a separate network stack for each persona. Virtual routing and forwarding (VRF) may be used to achieve this. VRF allows multiple instances of routing tables to exist and work simultaneously. When combined with network name spaces, a Linux kernel feature, VRF may create a completely isolated network stack from the device level to the software level, according to one or more non-limiting examples. As a result, during transition periods between personas **316**A and **316**B, or even if personas **316**A and **316**B are running at the same time, in these examples, communication data of each person **316**A and **316**B may be handled by completely isolated processes in separate memory spaces, so the data from the personas **316**A and **316**B do not traverse overlapping paths or share any queues or network resources.

Communication manager **318** may employ different technologies to improve the quality of communication, such as link failover, optimal link selection, load balancing, and/or data prioritization. Communication manager **318** may configure and control whether any of these technologies are used, and when, for each persona **316**A and **316**B. In some instances, communication manager **318** may provide such configuration and/or control in response to receiving user input (e.g., input from an administrator).

As one example, for each persona **316**A and **316**B, an administrator can decide which media (e.g., wireless (Wi-Fi), wired (Ethernet)) can be used with each respective persona. Each link can use its own encryption keys (and VPN tunnel(s)) depending on the active persona using encryption modules **352**, recognizing that different VPN gateways serve personas in different security domains, and that even personas in the same security domain may not be allowed access to the same gateways, depending on the user role. Regardless of the active persona and the available links, communication manager **318** may ensure (e.g., using encryption modules **352**) that the data is always encrypted using the correct keys without, in many cases, any user intervention or persona knowledge.

In certain examples, communication manager **318** may implement data prioritization and/or categorization using one or more data categorizers **354**. Communication manager **318** may also implement various link functions, such as link failover, optimal link selection, and/or load balancing, using one or more link managers **350** and/or one or more network interface modules **356**. Link managers **350** and/or network interface modules **356** may, in some examples, continuously monitor the quality of each link and assign different metrics to each link based on bandwidth, packet loss, and/or latency or other characteristics of the respective link and associated communication network. Various criteria, such as the ones described above, may be used by link managers **350** and/or network interface modules **356** to determine which link or communication network may be used at any point in time for data communication with a given persona. In some examples, link managers **350** and/or network interface modules **356** may make policy-based routing decisions to utilize the best media for the specific needs of various data types. For example, Voice-over-Internet Protocol (VoIP) may require a low latency media, and low bandwidth, whereas data downloads may require high bandwidth but not necessarily low latency. Link managers **350** and/or network interface modules **356** may also monitor for the detection of unreliable links. If the quality of a link degrades below a certain level (e.g., as signified by high packet loss or no connectivity at all), any communication going through that link may be diverted to another link if available. This transparent failover capability allows communication to be redirected to a new media without the knowledge of personas **316**A or **316**B. Because failover can be performed in a matter of seconds, applications in an active persona will not notice the temporary loss of connectivity as connections previously routed over failed media are rerouted.

Different techniques may be used to monitor link availability and/or quality (e.g., metrics associated with bandwidth, packet loss, and/or latency). At the basic connectivity level, link managers **350** and/or network interface modules **356** may send Internet Control Message Protocol (ping) or similar packets to the configured VPN gateways and accumulate statistics for each link over time. If the dropped ping packets exceed a threshold, the link is deemed to be down and the communication is switched over to another link. If the connection is restored over the link, the communication may be resumed over the link.

Another technique is monitoring the active communication sessions, allowing metrics (e.g., metrics associated with bandwidth, packet loss, and/or latency) to be derived from user traffic with no additional load and/or minimal impact. For instance, to collect session-based metrics, confederate network monitors or agents near the VPN client and gateway, or VPN clients and gateways augmented to identify flows and that work together as confederates or agents, in cooperation with link managers **350** and/or network interface modules **356**, may measure latency, packet loss, and/or bandwidth using existing traffic. (Examples of such clients and gateways are illustrated in FIGS. **4**A-**4**D.) Techniques can take advantage of user Transmission Control Protocol (TCP) flows, using TCP acknowledgements (ACKs), to time the packet delivery time over a media and derive bandwidth, packet loss, and/or latency based on many combined packet measurements, or it can involve small synthetic ACKs between confederates or agents, regardless of whether TCP flows can be distinguished or all flows are encrypted.

When existing traffic may not be sufficient to establish reliable metrics, confederates or agents may send/receive synthetic packets to/from the gateway. The state of each flow may be maintained to help establish better metrics over time. Link managers **350** and/or network interface modules **356** may keep an additional set of statistics based on latency, packet loss, and/or bandwidth to actual server addresses, before a second layer of encryption using encryption modules **352** to the gateways takes place, making end-to-end metric estimates possible. This may help link managers **350** and/or network interface modules **356** pick the optimal path not only based on the link metric to the next hop, but the quality of the route from the VPN gateway to the actual server. In such fashion, link managers **350** and/or network interface modules **356**, in cooperation with confederate network monitors or agents that are located remotely from the mobile computing device, may measure metrics associated with such items as bandwidth, packet loss, and latency, with potentially minimal impact, of monitored data flows produced by user applications, such as personas **316**A and **316**B shown in FIG. **3**, in order to characterize one or more available communication networks (e.g., one or more of networks **122** shown in FIG. **1**; one or more of networks **222** shown in FIG. **2**). The remote confederate network monitors or agents may, in some cases, be configured to passively monitor packets in a given flow, and link managers **350** and/or network interface modules **356**, in cooperation with these confederate network monitors or agents, may measure the time-of-transit of variously sized packets to estimate bandwidth, packet loss, and/or latency.

If more than one link is available at the same time, link managers **350** and/or network interface modules **356** may route the packets based on certain other criteria, such as the type of communication and administratively configured priority, using, for example, data categorizers **354**. As one example, a VoIP call may require low latency, and it may be routed through the link with the lowest latency metric. A big file download on the other hand, can be served by a high-bandwidth link, even if the link does not necessarily have low latency. If several flows are competing on the same link, and the link cannot potentially accommodate them all simultaneously, data categorizers **354** may, in some cases, apply a priority-based selection, where the flow with the higher priority is serviced first while the others are throttled, queued, or directed to an alternative link. In some cases, data categorizers **354** may assign priorities to flows based on the type of data being communicated (e.g., based on data type or category) and/or based on the persona (e.g., classified persona versus an unclassified persona) that is the source of the data.

FIGS. **4A-4D** are block diagrams illustrating example flows of information from a communication manager **418** of a mobile computing device **412** to external classified and unclassified servers, in accordance with one or more aspects of the present disclosure. In the examples of FIGS. **4A-4D**, mobile computing device **412** may be one example of mobile computing device **112** (FIG. **1**) and/or computing device **212** (FIG. **2**), and communication manager **418** may be one example of communication manager **118** (FIG. **1**), communication manager **218** (FIG. **2**), and/or communication manager **318** (FIG. **3**). The non-limiting examples illustrated in FIGS. **4A-4D** are shown for purposes of illustration only.

As shown in these figures, mobile computing device **412** may include a classified persona virtual machine guest OS environment **416**A and an unclassified persona virtual machine guest OS environment **416**B. (For purposes of brevity, the secure virtual machine host environment provided by mobile computing device **412** is not shown in these figures.) Classified persona virtual machine guest OS environment **416**A may comprise a virtual machine and may be one example of application environment **116**A (FIG. **1**), first persona **216**A (FIG. **2**), and/or first persona **316**A (FIG. **3**). Unclassified persona virtual machine guest OS environment **416**B may comprise a virtual machine and may be one example of application environment **116**B (FIG. **1**), first persona **216**B (FIG. **2**), and/or first persona **316**B (FIG. **3**).

Communication manager **418** may include one or more link managers **450**, one or more data categorizers **454**, one or more encryption modules **452**, and network interface modules **456**. Link managers **450** may be one example of link managers **350** (FIG. **3**), data categorizers **454** may be one example of data categorizers **354** (FIG. **3**), encryption modules **452** may be one example of encryption modules **352** (FIG. **3**), and network interface modules **456** may be one example of network interface modules **356** (FIG. **3**). In the non-limiting examples shown in FIGS. **4A-4D**, network interface modules **456** include a classified Ethernet client **458**, an unclassified Ethernet client **460**, a classified wireless client **462**, and an unclassified wireless client **464**. Each of classified Ethernet client **458** and classified wireless client **462** may be assigned to or otherwise associated with classified persona **416**A, while unclassified Ethernet client **460** and unclassified wireless client **464** may be assigned to or otherwise associated with unclassified persona **416**B.

Classified Ethernet client **458** and unclassified Ethernet client **460** are examples of wired clients and are each configured to communicate via Ethernet network **422**B. However, classified Ethernet client **458** is configured to communicate with classified Ethernet gateway **466** via Ethernet network **422**B, while unclassified Ethernet client **460** is configured to communicate with unclassified Ethernet gateway **472** via Ethernet network **422**B.

Classified wireless client **462** and unclassified wireless client **464** are each configured to communicate with wireless network **422**A (e.g., Wi-Fi network). However, classified wireless client **462** is configured to communicate with classified wireless gateway **470** via wireless network **422**A, while unclassified wireless client **464** is configured to communicate with unclassified wireless gateway **476** via wireless network **422**A.

Classified Ethernet gateway **466** and classified wireless gateway **470** are configured to communicate with one or more classified web and file servers **468**. Unclassified Ethernet gateway **472** and unclassified wireless gateway **476** are configured to communicate with one or more unclassified web and file servers **474**.

In the examples of FIGS. **4A-4D**, communication manager **418** is enabled to leverage two different media, namely wired (Ethernet) and wireless media, and to automatically react to changing media environments, as will be described in further detail below. Communication manager **418** may also monitor latency for the two media and automatically switch all traffic to the media with the lowest latency in various cases, ensuring the best link is used if both are available. Mobile computing device **412** is configured to host two personas in the non-limiting examples of FIGS. **4A-4D**: one in the classified security domain (classified persona **416**A), and one in the unclassified security domain (unclassified persona **416**B). Classified web and file servers **468** are communicatively coupled to classified Ethernet gateway **466** and classified wireless gateway **470**, which may be completely isolated from unclassified web and file servers **474**, unclassified Ethernet gateway **472**, and unclassified wireless gateway **476**. Access to classified web and file servers **468** occurs via one or more secure VPN gateways, either using classified Ethernet gateway **466** or classified wireless gateway **470**, using corresponding authentication and encryption keys, which may be stored and accessed by communication manager **418**, and which, in various examples, may be inaccessible directly by personas **416**A and **416**B. Different keys may be associated with each VPN gateway, and any attempt to access a gateway by a system without the appropriate keys may be denied by the respective gateway, providing administrative control over entities having access to each security domain.

In the illustrated examples, classified Ethernet client **458** of network interface modules **456** (in communication manager **418**) may control communications with classified Ethernet gateway **466** via Ethernet network **422**B, and may manage a first group of authentication and encryption keys that are associated with classified Ethernet gateway **466**. Unclassified Ethernet client **460** may control communications with unclassified Ethernet gateway **472** via Ethernet network **422**B, and may manage a second group of authentication and encryption keys associated with unclassified Ethernet gateway **472**. Classified wireless client **462** may control communications with classified wireless gateway **470** via wireless network **422**A, and may manage a third group of authentication and encryption keys associated with classified wireless gateway **470**. Unclassified wireless client **464** may control communications with unclassified wireless gateway **476** via wireless network **422**A, and may manage a fourth group of authentication and encryption keys associated with unclassified wireless gateway **476**.

Communication manager **418** may only allow communication between mobile computing device **412** and the authorized VPN gateways (e.g., one of classified Ethernet gateway **466**, classified wireless gateway **470**, unclassified Ethernet gateway **472**, unclassified wireless gateway **476**) to ensure mobile computing device **412** only accesses servers or other endpoints of a known classification level matching the active persona. Thus, if classified persona **416**A is the currently active persona, communication manager **418** ensures that either classified Ethernet client **458** or classified wireless client **462** is used to securely communicate (e.g., via a respective VPN) with classified web and file servers **468** via either classified Ethernet gateway **466** or classified wireless gateway **470**, respectively. On the other hand, if unclassified persona **416**B is the active persona, communication manager **418** ensures that either unclassified Ethernet client **460** or unclassified wireless client **464** is used to securely communicate (e.g., via a respective VPN) with unclassified web and file servers **474** via either unclassified Ethernet gateway **472** or unclassified wireless gateway **476**, respectively. In various examples, each of classified Ethernet gateway **466**, classified wireless gateway **470**, unclassified Ethernet gateway **472**, and unclassified wireless gateway **476** may comprise a respective VPN gateway.

In various examples, classified persona **416**A and classified web and file servers **468** appear to be on the same local network. Similarly, unclassified persona **416**B and unclassified web and file servers **474** appear to be on a different local network. This highlights the fact that each persona **416**A and **416**B may not have information regarding how packets get to and from the respective servers **468** and **474**. For example, from its perspective, classified persona **416**A may be directly attached to the secure site infrastructure provided by classified web and file servers **468**. Similarly, from its perspective, unclassified persona **416**B may be directly attached to the secure site infrastructure provided by unclassified web and file servers **474**.

As particularly illustrated in FIG. **4**A, it is assumed that classified persona **416**A is the currently active persona, and it is also assumed that Ethernet network **422**B is available. As a result, communication manager **418** selects classified Ethernet client **458** to communicate with classified web and file servers **468** via Ethernet network **422**B and classified Ethernet gateway **466**. Even if wireless network **422**A is available, communication manager **418** may, in various cases, select classified Ethernet client **458** over classified wireless client **462** if communication manager **418** determines that Ethernet network **422**B is preferred over wireless network **422**A (e.g., based on speed, bandwidth, latency, reliability, data category/priority, and/or other criteria). Certain examples of data category or data type may include VoIP, file downloads, or email. Bandwidth and/or latency requirements may be dependent on the data category or priority, in many cases. Classified Ethernet client **458** may utilize one or more authentication and encryption keys to communicate with classified Ethernet gateway **466**. A second layer of encryption and/or authentication may be provided by classified persona **416**A and classified web and file servers **468**, such that classified persona **416**A and classified web and file servers **468** may utilize a separate group of authentication and/or encryption keys that is applied to exchanged data.

As noted earlier, communication manager **418** may also select one of network interface modules **456** based on one or more criteria, such as one or more of the criteria described above. As one non-limiting example, communication manager **418** may select one or network interface modules **456** based on the priority and/or categorization of data that is being sent from a persona, such as classified persona **416**A. In addition, if a persona, such as persona **416**A, includes various different applications, communication manager **418** may further base its decision on the specific application, or type of application, that is sending the data.

Continuing with the above example, at a given point in time, Ethernet network **422**B may become unavailable, or communication manager **418** may determine that wireless network **422**A has become a preferred network over Ethernet network **422**B (e.g., based on one or more of the example criteria described above).

In this example, if another communication network such as wireless network **422**A becomes available, communication manager **418** may select classified wireless client **462** to continue communication between classified persona **416**A and classified web and file servers **468**. Communication manager **418** and/or classified wireless client **462** may receive additional information that is associated with the security domain (e.g., classified domain) for classified persona **416**A, which may be provided by classified persona **416**A. Communication manager **418** and/or classified wireless client **462** may determine that this additional information is to be sent to classified web and file servers **468** via classified wireless gateway **470** (e.g., using a VPN). Communication manager **418** and/or classified wireless client **462** may encrypt the additional information, using mechanisms such as those described previously. As shown in FIG. **4**B, classified wireless client **462** communicates with classified wireless gateway **470** via wireless network **422**A, and classified wireless gateway **470** communicates with classified web and file servers **468**. As a result, classified persona **416**A is capable of maintaining seamless connectivity with classified web and file servers **468**, even after Ethernet network **422**B is unavailable, such that wireless network **422**A is used instead.

Continuing again with this example, at a subsequent time, Ethernet network **422**B may once again become available. At this stage, if communication manager **418** determines that Ethernet network **422**B is preferred over wireless network **422**A (e.g., based on speed, bandwidth, latency, reliability, data category/type/priority, and/or other criteria), communication manager **418** may again select classified Ethernet client **458** to resume data communication between classified persona **416**A and classified web and file servers **468** via Ethernet network **422**B and classified Ethernet gateway **466**.

If classified persona **416**A becomes disabled or suspended, and unclassified persona **416**B becomes the active persona, communication manager **418** determines whether to use unclassified Ethernet client **460** or unclassified wireless client **464** to enable communication between unclassified persona **416**B and unclassified web and file servers **474**. If Ethernet network **422**B is available, and communication manager **418** determines that Ethernet network **422**B is preferred over wireless network **422**A, communication manager **418** selects unclassified Ethernet client **460** to communicate with unclassified Ethernet gateway **472** and unclassified web and file servers **474** via Ethernet network **422**B, as shown in FIG. **4**C. If Ethernet network **422**B, at some point in time, is no longer available, or if communication manager **418** determines that wireless network **422**A has become a preferred network over Ethernet network **422**B, communication manager **418** may select unclassified wireless client **464** to communicate with unclassified wireless gateway **476** and unclassified web and file servers **474**, as shown in FIG. **4**D, enabling unclassified persona **416**B to continue interacting with unclassified web and file servers **474** in a seamless fashion.

FIG. **5** is a block diagram illustrating further details of an example computing device **512**, in accordance with one or more aspects of the present disclosure. FIG. **5** illustrates only one particular example of computing device **512**, and many other examples of computing device **512** may be used in other instances and may include a subset of the components shown, or may include additional components not shown, in FIG. **5**. Mobile computing device **512** may be one example of mobile computing device **112** (FIG. **1**), mobile computing device **212** (FIG. **2**), and/or mobile computing device **412** (FIGS. **4**A-**4**D).

As shown in the example of FIG. **5**, mobile computing device **512** includes one or more processors **535**, one or more input devices **580**, one or more communication units **520**, one or more output devices **582**, and one or more storage devices **528**. Communication channels **584** may interconnect each of the components **535**, **520**, **582**, **580**, and **528** for inter-component communications (physically, communicatively, and/or operatively). In some examples, communication channels **584** may include a system bus, a network connection, an inter-process communication data structure, or any other method for communicating data between hardware and/or software.

One or more input devices **580** of mobile computing device **512** may receive input. Examples of input are tactile, audio, and video input. Examples of input devices **580** include a presence-sensitive screen, touch-sensitive screen, mouse, keyboard, voice responsive system, video camera, microphone or any other type of device for detecting input from a human or machine. Touchscreen **224** (FIG. **2**), cameras **226** (FIG. **2**), audio devices **232** (FIG. **2**), and/or buttons **234** (FIG. **2**) may be examples of input devices **580**.

One or more output devices **582** of mobile computing device **512** may generate output. Examples of output are tactile, audio, and video output. Examples of output devices **582** include a presence-sensitive screen, sound card, video graphics adapter card, speaker, cathode ray tube (CRT) monitor, liquid crystal display (LCD), or any other type of device for generating output to a human or machine. Output devices **582** may include display devices such as cathode ray tube (CRT) monitor, liquid crystal display (LCD), or any other type of device for generating tactile, audio, and/or visual output. Touchscreen **224** (FIG. **2**) and/or audio devices **232** (FIG. **2**) may be examples of output devices **582**.

One or more communication units **520** may communicate with one or more other computing systems or devices via one or more networks by transmitting and/or receiving network signals on the one or more networks. Examples of communication units **520** include a network interface card (e.g. such as an Ethernet card), an optical transceiver, a radio frequency transceiver, or any other type of device that can send and/or receive information, such as through a wired or wireless network. Other examples of communication units **520** may include short wave radios, cellular data radios, wireless Ethernet network radios, as well as universal serial bus (USB) controllers. Communication units **520** may provide wired and/or wireless communication. Communication units **120** (FIG. **1**) and/or communication units **220** (FIG. **2**) may be examples of communication units **520**.

One or more storage devices **528** may store information for processing during operation of mobile computing device **512** (e.g., mobile computing device **512** may store data accessed by one or more modules, processes, applications, or the like during execution at mobile computing device **512**). Storage devices **228** (FIG. **2**) are one example of storage devices **528**. In some examples, storage devices **528** may be configured for short-term storage of information as volatile memory and therefore not retain stored contents if powered off. Examples of volatile memories include random access memories (RAM), dynamic random access memories (DRAM), static random access memories (SRAM), and other forms of volatile memories known in the art.

Storage devices **528**, in some examples, also include one or more computer-readable storage media. Storage devices **528** may be configured to store larger amounts of information than volatile memory. Storage devices **528** may further be configured for long-term storage of information as non-volatile memory space and retain information after power on/off cycles. Examples of non-volatile memories include magnetic hard discs, optical discs, floppy discs, flash memories, or forms of electrically programmable memories (EPROM) or electrically erasable and programmable (EEPROM) memories. Storage devices **528** may store program instructions and/or data associated with one or more software/firmware elements or modules.

For example, when mobile computing device **512** comprises an example of mobile computing device **112** shown in FIG. **1**, storage devices **528** may store instructions and/or data associated with secure host environment **114**, application environments **116**, and communication manager **118**. When mobile computing device **512** comprises an example of mobile computing device **212** shown in FIG. **2**, storage devices **528** may store instructions and/or data associated with secure boot module **236**, secure virtual machine host environment **214**, personas **216**, control domain **243**, persona/resource manager **244**, communication manager **218**, and/or secure boot module **242**. Storage devices **528** may also store instructions and/or data associated with personas **316**, control domain **343**, communication manager **318**, link managers **350**, encryption modules **352**, data categorizers **354**, and/or network interface modules **356** (FIG. **3**). When mobile computing device **512** comprises an example of mobile computing device **412** shown in FIGS. **4**A-**4**D, storage devices **528** may store instructions and/or data associated with personas **416**, communication manager **418**, link managers **450**, data categorizers **454**, encryption modules **452**, and network interface modules **456**.

Mobile computing device **512** further includes one or more processors **535** that may implement functionality and/or execute instructions within mobile computing device **512**. For example, processors **535** may receive and execute instructions stored by storage devices **528** that execute the functionality of the elements and/or modules described herein. These instructions executed by processors **535** may cause mobile computing device **512** to store information within storage devices **528** during program execution. Processors **535** may also execute instructions of the operating system to perform one or more operations described herein. Processors **235** (FIG. **2**) may be one example of processors **535**.

FIG. **6** is a flow diagram illustrating an example process that may be performed by a mobile computing device, in accordance with one or more aspects of the present disclosure. For example, the process illustrated in FIG. **6**, which may comprise one or more operations, may be performed by one or more of the mobile computing devices shown in FIGS. **1**, **2**, **4**A-**4**D, and/or **5**, and/or a mobile computing device that includes the communication manager shown in FIG. **3**. For purposes of illustration only, it will be assumed that the process of FIG. **6** is performed by mobile computing device **112** shown in FIG. **1**.

As illustrated in the example process of FIG. **6**, mobile computing device **112** receives (**602**) an indication of a selection of a first application environment (e.g., application environment **116**A) from a plurality of application environments, where the first application environment comprises a first virtual environment (e.g., virtual machine, container) that is associated with a first security domain (e.g., classified domain), and where the first application environment is not currently executing on mobile computing device **112**. Responsive to receiving the indication of the selection of the first application environment, mobile computing device **112** suspends (**604**) execution of a second application environment (e.g., application environment **116**N) from the plurality of application environments, where the second application environment is different from the first application environment, and where the second application environment comprises a second virtual environment (e.g., virtual machine, container) that is associated with a second security domain (e.g., unclassified security domain) different from the first security domain.

After suspending execution of the second application environment, mobile computing device **112** initiates (**606**) execution of the first application environment on mobile computing device **112**, where the first application environment is configured to isolate execution of one or more software applications within the first application environment, and mobile computing device **112** identifies (**608**) information associated with the first security domain and provided by the first application environment that is to be sent to an external computing device associated with the first security domain. Mobile computing device **112** selects (**610**) at least one communication network from one or more communication networks (e.g., networks **122**) that are each available to mobile computing device **112** for data communication, wherein selecting the at least one communication network is based on one or more criteria associated with at least one of the information associated with the first security domain or the one or more communication networks. Mobile computing device **112** encrypts (**612**), based on the first security domain and the at least one selected communication network, the information to generate encrypted information associated with the first security domain, and sends (**614**), to the external computing device, via the at least one selected communication network, the encrypted information. In certain cases, mobile computing device **112** may encrypt the information to generate the encrypted information associated with the first security domain further based on the at least one communication network.

In some examples, the first security domain may be a classified security domain, and the first application environment may be a persona (e.g., application environment **116**A, persona **216**A) associated with the classified security domain. The second security domain may be an unclassified security domain, and the second application environment may be a persona (e.g., application environment **116**B, persona **216**B shown in FIG. **2**) associated with the unclassified security domain.

In some examples, the first virtual environment comprises a first virtual machine environment, and the second virtual environment comprises a second virtual machine environment. In some examples, the one or more criteria may be associated with at least one of latency characteristics, bandwidth characteristics, or packet loss characteristics associated with the at least one selected communication network. Mobile computing device **112** may, in some cases, in cooperation with one or more agents located remotely from mobile computing device **112**, measure the at least one of the latency characteristics, the bandwidth characteristics, or the packet loss characteristics of one or more monitored data flows that are produced by the first application environment, in order to characterize the one or more communication networks. The one or more criteria may, in certain cases, be associated with at least one of a data category or a priority associated with the information associated with the first security domain that is to be sent to the external computing device.

In some examples, the one or more communication networks may comprise one or more wired networks (e.g., one or more of wired networks **222**B shown in FIG. **2**) and one or more wireless networks (e.g., one or more of wireless networks **222**A). Selecting the at least one communication network may include selecting the at least one communication network based on one or more load balancing criteria associated with the one or more communication networks.

In some examples, mobile computing device **112** may select an external gateway (e.g., one of gateways **466**, **470**, **472**, or **476** shown in FIGS. **4**A-**4**D) that is communicatively coupled to the external computing device, and create a virtual private network across the at least one selected communication network that includes mobile computing device **112** and the external gateway. The virtual private network is associated with the first security domain, and mobile computing device **112** may send the encrypted information to the external gateway using the virtual private network.

In some examples, the at least one selected communication network comprises a first communication network, and the one or more communication networks comprise a plurality of communication networks. After sending the encrypted information, mobile computing device **112** may determine that the first communication network is no longer available to mobile computing device **112** for data communication. Mobile computing device **112** may select a second communication network that is available to mobile computing device **112** for data communication, the second communication network being different than the first communication network. Mobile computing device **112** may identify additional information associated with the first security domain and provided by the first application environment that is to be sent to the external computing device, and may encrypt, based on the first security domain, the additional information to generate encrypted additional information associated with the first security domain. Mobile computing device **112** may send, to the external computing device, via the second communication network, the encrypted additional information.

In some examples, after suspending execution of the second application environment, mobile computing device **112** may store state information associated with one or more resources of mobile computing device **112**, which were previously used by the second application environment. Mobile computing device **112** may prohibit any communication with the second application environment. Mobile computing device **112** may prohibit the first application environment from modifying a virtual disk image associated with the second application environment.

In some examples, mobile computing device **112** may provide a virtual disk image associated with the first application environment, where the virtual disk image comprises a physical partition of a storage device or a file image, and where the virtual disk image includes state information associated with the first application environment. In some cases, mobile computing device **112** may provide a virtual disk image, where the virtual disk image comprises multiple physical partitions of one or more storage devices or multiple file images. Mobile computing device **112** may protect at least a portion of the virtual disk image from modification by the first application environment.

In some examples, mobile computing device **112** may provide a virtual disk image that is associated with the first application environment and with the second application environment. Mobile computing device **112** may assign, to the first application environment, first access rights to the virtual disk image, and may assign, to the second application environment, second access rights to the virtual disk image. One of the first access rights or the second access rights may comprise read-only access rights, and the other one of the first access rights or the second access rights may comprise at least write access rights (e.g., read-write), such that mobile computing device **112** may effectively enable one-way communication of information via the virtual disk image between the first application environment and with the second application environment.

In some examples, mobile computing device **112** may limit access of the first application environment to one or more resources of mobile computing device **112** by providing at least one virtualized communication channel between the first application environment and a communication manager (e.g., communication manager **118**) executing on the mobile computing device. The communication manager controls the at least one virtualized communication channel, and the communication manger operates in a separate execution domain with respect to the first application environment. The communication manager may select the at least one communication network from one or more available physical communication networks, and select one or more gateways (e.g., one or more of gateways **466**, **470**, **472**, **472** illustrated in FIGS. **4**A-**4**D) per selected communication network for use in one or more virtual private networks.

In some examples, the communication manager may execute on mobile computing device **112** in a virtual environment that is isolated from the first application environment and from the second application environment. The communication manager may be configured to be modified only via encrypted communication with an administrative device that is located remotely from mobile computing device **112**.

In one or more examples, the functions described may be implemented in hardware, software, firmware, or any combination thereof. If implemented in software, the functions may be stored on or transmitted over, as one or more instructions or code, a computer-readable medium and executed by a hardware-based processing unit. Computer-readable media may include computer-readable storage media, which corresponds to a tangible medium such as data storage media, or communication media including any medium that facilitates transfer of a computer program from one place to another, e.g., according to a communication protocol. In this manner, computer-readable media generally may correspond to (1) tangible computer-readable storage media, which is non-transitory or (2) a communication medium such as a signal or carrier wave. Data storage media may be any available media that can be accessed by one or more computers or one or more processing units (e.g., processors) to retrieve instructions, code and/or data structures for implementation of the techniques described in this disclosure. A computer program product may include a computer-readable medium.

By way of example, and not limitation, such computer-readable storage media can comprise random access memory (RAM), read-only memory (ROM), electrically erasable programmable read-only memory (EEPROM), compact disc read-only memory (CD-ROM) or other optical disk storage, magnetic disk storage, or other magnetic storage devices, flash memory, or any other storage medium that can be used to store desired program code in the form of instructions or data structures and that can be accessed by a computer. Also, any connection is properly termed a computer-readable medium. For example, if instructions are transmitted from a website, server, or other remote source using a coaxial cable, fiber optic cable, twisted pair, digital subscriber line (DSL), or wireless technologies such as infrared, radio, and microwave, then the coaxial cable, fiber optic cable, twisted pair, DSL, or wireless technologies such as infrared, radio, and microwave are included in the definition of medium. It should be understood, however, that computer-readable storage media and data storage media do not include connections, carrier waves, signals, or other transient media, but are instead directed to non-transient, tangible storage media. Disk and disc, as used herein, includes compact disc (CD), laser disc, optical disc, digital versatile disc (DVD), floppy disk and Blu-ray disc, where disks usually reproduce data magnetically, while discs reproduce data optically with lasers. Combinations of the above should also be included within the scope of computer-readable media.

Instructions may be executed by one or more processing units (e.g., processors), such as one or more digital signal processors (DSPs), general purpose microprocessors, application specific integrated circuits (ASICs), field programmable logic arrays (FPGAs), or other equivalent integrated or discrete logic circuitry. Accordingly, the term "processing unit" or "processor," as used herein may refer to any of the foregoing structure or any other structure suitable for implementation of the techniques described herein. In addition, in some aspects, the functionality described herein may be provided within dedicated hardware and/or software modules. Also, the techniques could be fully implemented in one or more circuits or logic elements.

The techniques of this disclosure may be implemented in a wide variety of devices or apparatuses, including a wireless handset, an integrated circuit (IC) or a set of ICs (e.g., a chip set). Various components, modules, or units are described in this disclosure to emphasize functional aspects of devices configured to perform the disclosed techniques, but do not necessarily require realization by different hardware units. Rather, as described above, various units may be combined in a hardware unit or provided by a collection of interoperative hardware units, including one or more processing units as described above, in conjunction with suitable software and/or firmware.

It is to be recognized that, depending on the embodiment, certain acts or events of any of the methods described herein can be performed in a different sequence, may be added, merged, or left out altogether (e.g., not all described acts or events are necessary for the practice of the method). Moreover, in certain embodiments, acts or events may be performed concurrently, e.g., through multi-threaded processing, interrupt processing, or multiple processing units, rather than sequentially.

In some examples, a computer-readable storage medium comprises a non-transitory medium. The term "non-transitory" indicates that the storage medium is not embodied in a carrier wave or a propagated signal. In certain examples, a non-transitory storage medium may store data that can, over time, change (e.g., in RAM or cache).

Various examples have been described. These and other examples are within the scope of the following claims.

What is claimed is:

1. A mobile computing device, comprising:

one or more processors; and

a computer-readable storage device communicatively coupled to the one or more processors, wherein the computer-readable storage device stores instructions that, when executed by the one or more processors, cause the one or more processors to:

responsive to receiving an indication of a selection of a first application environment from a plurality of application environments, suspend execution of a second application environment from the plurality of application environments, wherein the first application environment comprises a first virtual environment that is associated with a first domain, and wherein the second application environment comprises a second virtual environment that is associated with a second domain different from the first domain;

initiate execution of the first application environment, wherein the first application environment is configured to isolate execution of one or more software applications within the first application environment;

limit access of the first application environment to one or more resources of the mobile computing device that are allocated to the first application environment during execution;

select, based on one or more criteria associated with one or more data types, a plurality of different communication networks, including selecting, based on the one or more criteria, a first communication network for communication of first data having a first data type and selecting, based on the one or more criteria, a second communication network for communication of second data having a second data type that is different than the first data type, wherein the one or more criteria at least include one or more load balancing criteria that are associated with a current availability of the plurality of different communication networks for data communication with the mobile computing device; and

send, to one or more external computing devices, and via the plurality of different communication networks, data provided by the first application environment, including sending, to the one or more external computing devices and via the first communication network, the first data provided by the first application environment and sending to the one or more external computing devices and via the second communication network, the second data provided by the first application environment, wherein the one or more external computing devices are also associated with the first domain.

2. The mobile computing device of claim **1**, wherein the plurality of different communication networks includes one or more of at least one wireless network or at least one wired network.

3. The mobile computing device of claim **2**, wherein the at least one wireless network includes a plurality of different wireless networks.

4. The mobile computing device of claim **1**,

wherein the instructions stored by the computer-readable storage device that cause the one or more processors to select the plurality of different communication networks cause the one or more processors to select, based on the one or more criteria, three or more different communication networks, and

wherein the instructions stored by the computer-readable storage device that cause the one or more processors to send the data provided by the first application environment cause the one or more processors to send, to the one or more external computing devices, and via the three or more different communication networks, the data provided by the first application environment.

5. The mobile computing device of claim **1**, wherein the instructions stored by the computer-readable storage device further cause the one or more processors to:

initiate execution of a third application environment that comprises a third virtual environment; and

send, via at least one of the plurality of different communication networks, data provided by the third application environment.

6. The mobile computing device of claim **5**,

wherein the third virtual environment of the third application environment is also associated with the first domain, and

wherein the instructions stored by the computer-readable storage device that cause the one or more processors to send the data provided by the third application environment cause the one or more processors to send, to the one or more external computing devices via at least one of the plurality of different communication networks, the data provided by the third application environment.

7. The mobile computing device of claim **1**, wherein the one or more criteria are further associated with one or more of (a) a categorization or priority of the data provided by the first application environment, (b) a type of each of the plurality of different communication networks, (c) latency characteristics of each of the plurality of different communication networks, (d) speed characteristics of each of the plurality of different communication networks, (e) bandwidth characteristics of each of the plurality of different communication networks, (f) packet loss characteristics of each of the plurality of different communication networks, or (g) the one or more software applications executing in the first application environment.

8. The mobile computing device of claim **1**, wherein the plurality of different communication networks includes a first communication network and a second communication network, and wherein the instructions stored by the computer-readable storage device further cause the one or more processors to:

determine that the first communication network of the plurality of different communication networks is no longer available to the mobile computing device for data communication;

select, based on the one or more criteria, a third communication network from the plurality of different communication networks that is available to the mobile computing device for data communication; and

send, to the one or more external computing devices, and via the second and third second communication networks, additional data provided by the first application environment.

9. The mobile computing device of claim **1**, wherein the instructions stored by the computer-readable storage device further cause the one or more processors to:

provide a virtual disk image associated with the second application environment, wherein the virtual disk image comprises at least one file image or at least one physical partition of at least one storage device; and

prohibit the first application environment from modifying the virtual disk image associated with the second application environment.

10. The mobile computing device of claim **1**, wherein the instructions stored by the computer-readable storage device further cause the one or more processors to:

provide a virtual disk image that is associated with the first application environment and with the second application environment;

assign, to the first application environment, first access rights to the virtual disk image; and

assign, to the second application environment, second access rights to the virtual disk image,

wherein one of the first access rights or the second access rights comprises read-only access rights, and wherein another one of the first access rights or the second access rights comprises at least write access rights, such that the mobile computing device enables one-way communication of information via the virtual disk image between the first application environment and with the second application environment.

11. The mobile computing device of claim 1, wherein the instructions stored by the computer-readable storage device further cause the one or more processors to:

limit access of the first application environment to one or more resources of the mobile computing device at least by providing one or more virtualized communication channels between the first application environment and a communication manager executing on the mobile computing device, wherein the communication manager controls the one or more virtualized communication channels, wherein the communication manger manager operates in a separate execution domain with respect to the first application environment.

12. A method comprising:

responsive to receiving an indication of a selection of a first application environment from a plurality of application environments, suspending, by a mobile computing device, execution of a second application environment from the plurality of application environments, wherein the first application environment comprises a first virtual environment that is associated with a first domain, and wherein the second application environment comprises a second virtual environment that is associated with a second domain different from the first domain;

initiating, by the mobile computing device, execution of the first application environment, wherein the first application environment is configured to isolate execution of one or more software applications within the first application environment;

limiting, by the mobile computing device, access of the first application environment to one or more resources of the mobile computing device that are allocated to the first application environment during execution;

selecting, by the mobile computing device and based on one or more criteria associated with one or more data types, a plurality of different communication networks, including selecting, based on the one or more criteria, a first communication network for communication of first data having a first data type and selecting, based on the one or more criteria, a second communication network for communication of second data having a second data type that is different than the first data type, wherein the one or more criteria at least include one or more load balancing criteria that are associated with a current availability of the plurality of different communication networks for data communication with the mobile computing device; and

sending, by the mobile computing device and to one or more external computing devices, and via the plurality of different communication networks, data provided by the first application environment, including sending, to the one or more external computing devices and via the first communication network, the first data provided by the first application environment and sending to the one or more external computing devices and via the second communication network, the second data provided by the first application environment, wherein the one or more external computing devices are also associated with the first domain.

13. The method of claim 12,

wherein selecting the plurality of different communication networks comprises selecting, by the mobile computing device and based on the one or more criteria, three or more different communication networks, and

wherein sending the data provided by the first application environment comprises sending, by the mobile computing device and to the one or more external computing devices, via the three or more different communication networks, the data provided by the first application environment.

14. The method of claim 12, further comprising:

initiating, by the mobile computing device, execution of a third application environment that comprises a third virtual environment; and

sending, by the mobile computing device, via at least one of the plurality of different communication networks, data provided by the third application environment.

15. The method of claim 12, wherein the plurality of different communication networks includes a first communication network and a second communication network, and wherein the method further comprises:

determining, by the mobile computing device, that the first communication network of the plurality of different communication networks is no longer available to the mobile computing device for data communication;

selecting, by the mobile computing device and based on the one or more criteria, a third communication network from the plurality of different communication networks that is available to the mobile computing device for data communication; and

sending, by the mobile computing device and to the one or more external computing devices, via the second and third second communication networks, additional data provided by the first application environment.

16. A computer-readable storage device storing instructions that, when executed, cause one or more processors of a mobile computing device to:

responsive to receiving an indication of a selection of a first application environment from a plurality of application environments, suspend execution of a second application environment from the plurality of application environments, wherein the first application environment comprises a first virtual environment that is associated with a first domain, and wherein the second application environment comprises a second virtual environment that is associated with a second domain different from the first domain;

initiate execution of the first application environment, wherein the first application environment is configured to isolate execution of one or more software applications within the first application environment;

limit access of the first application environment to one or more resources of the mobile computing device that are allocated to the first application environment during execution;

select, based on one or more criteria associated with one or more data types, a plurality of different communication networks, including selecting, based on the one or more criteria, a first communication network for communication of first data having a first data type and selecting, based on the one or more criteria, a second communication network for communication of second data having a second data type that is different than the first data type, wherein the one or more criteria at least include one or more load balancing criteria that are associated with a current availability of the plurality of different communication networks for data communication with the mobile computing device; and send, to one or more external computing devices, and via the plurality of different communication networks, data provided by the first application environment, including sending, to the one or more external computing devices and via the first communication network, the first data provided by the first application environment and sending to the one or more external computing devices and via the second communication network, the second data provided by the first application environment, wherein the one or more external computing devices are also associated with the first domain.

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